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**A COMPUTER MODEL OF THE TILTING PAD JOURNAL
BEARING SUITABLE FOR THE MICRO-COMPUTER
PART 2: DYNAMIC ANALYSIS**

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A COMPUTER MODEL OF THE TILTING PAD
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PART 2: DYNAMIC ANALYSIS

MODÈLE INFORMATIQUE DU PALIER LISSE À COUSSINETS PIVOTANTS
COMPATIBLE AVEC LE MICRO-ORDINATEUR
PARTIE 2: ANALYSE DYNAMIQUE

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Technical Report

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ABSTRACT

A theoretical study on the steady state and dynamic behaviour of the tilting pad journal bearing has been undertaken. A computer model, developed by NRC, considers the entire bearing and allows for the inclusion of thermal and elastic distortions, variable viscosity, hot oil carry over and turbulence within the oil film.

Part 1 of the study considers the steady state analysis and results are verified against five sets of independent data. This second report examines bearing dynamic behaviour and presents stiffness and damping coefficients for the five shoe, tilting pad journal bearing. The effects of changing bearing preload and direction of loading are illustrated.

This report also describes the theoretical basis of the computer model and includes a full listing of the program.

RÉSUMÉ

Une étude théorique sur le comportement dynamique et en régime permanent du palier lisse à coussinets pivotants a été entreprise. Un modèle informatique, mis au point par le CNRC, considère l'ensemble du palier et tient compte des déformations thermiques et élastiques, de la viscosité variable, de la tenue de l'huile à haute température et de la turbulence dans le film de fluide.

La partie 1 de l'étude porte sur l'analyse du palier en régime permanent et les résultats sont vérifiés contre cinq ensembles de données indépendantes. Ce deuxième rapport traite du comportement dynamique du palier et renferme des coefficients de rigidité et d'amortissement pour le palier lisse à cinq coussinets pivotants. Les effets de modifications de la charge initiale et de la répartition de la charge en régime de fonctionnement sont illustrés.

Le présent rapport décrit aussi la base théorique du modèle informatique et renferme un listage complet du programme.



CONTENTS

	Page
ACKNOWLEDGEMENT	(ii)
ABSTRACT/RESUME	(iii)
LIST OF ILLUSTRATIONS	(v)
LIST OF APPENDICES	(v)
LIST OF SYMBOLS	(vi)
1.0 INTRODUCTION	1
2.0 BEARING DYNAMICS	1
3.0 SPRING AND DAMPING COEFFICIENTS	2
4.0 COMPUTER MODEL-HANDRUN	3
4.1 Steady State Analysis	3
4.2 Dynamic Analysis	4
4.2.1 Stiffness coefficients	4
4.2.2 Damping coefficients	5
5.0 DISCUSSION	6
5.1 Preload and Bearing Clearances	6
5.2 Loading Conditions	7
5.3 Program Verification	7
6.0 CONCLUSIONS	8
7.0 FURTHER WORK	8
8.0 REFERENCES	9
DOCUMENTATION PAGE	

CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

Figure	Page
1 Tapered oil film	10
2 Bearing preload	10
3 Effect of clearances on film shape	11
4 'On pad' and 'between pads' loading conditions	11
5 Stiffness coefficients for the zero and 0.5 preloaded bearings. Load 'on pad', central pivot	12
6 Damping coefficients for the zero and 0.5 preloaded bearings. Load 'on pad', central pivot	13
7 Effect of different loading conditions on the stiffness coefficients. Zero preload, central pivot	14
8 Effect of different loading conditions on the damping coefficients. Zero preload, central pivot	15

LIST OF APPENDICES

Appendix

A Description of Subroutines and Program Listing	A1
B Derivation of PSISTEP and EQCSTEP	B1

LIST OF SYMBOLS

Symbol		Units
δ	Pad surface deviation	m
ϵ	Shaft eccentricity ratio (e/cl)	
θ	Circumferential coordinate	rad.
μ	Absolute viscosity	N.sec/m ²
ρ	Density	N/m ³
τ	Shear stress at journal surface	N/m ²
ψ	Attitude angle	rad
ω	Angular velocity	rad/sec
Axx, Ayy	Horizontal, vertical bearing stiffnesses	N/m
Axy, Ayx	Cross-coupled bearing stiffnesses	N/m
Axx', Ayy'	Dimensionless stiffness coefficients	
Axy', Ayx'	($A_{xx} \frac{cp}{W}$ etc.)	
a	Heat loss coefficient	
B	Pad axial width	m
Bxx, Byy	Horizontal, vertical bearing damping	N.sec/m
Bxy, Byx	Cross-coupled bearing damping	N.sec/m
Bxx', Byy'	Dimensionless damping coefficients	
Bxy', Byx'	($B_{xx} \frac{cp}{W \cdot \omega}$ etc.)	
cl	Bearing radial clearance ($R_b - R$)	m
cp	Pad radial clearance ($R_p - R$)	m
Cf	Couette shear stress factor	
Cp	Oil specific heat	J/N/°C
D	Bearing diameter	m
e	Shaft eccentricity	m
G _x , G _z	Turbulence factors	
h	Oil film thickness	m
m	Pad preload factor ($1 - \frac{cl}{cp}$)	
p	Oil film pressure	N/m ²
q _x , q _z	Volume flows in x, z coordinates	m ³ /sec
R	Shaft radius	m
R _b	Radius from bearing centre to pivot	m
Re	Reynolds number ($\rho U h / \mu$)	
R _p	Pad radius of curvature	m
S	Sommerfeld Number $\frac{\mu N D B}{W} \frac{R}{C_p}^2$	
t	Time	sec
T	Temperature	°C
U	Shaft velocity	m/sec
W	Bearing load	Newtons
x, z	Circumferential, axial coordinates	
x, y	Horizontal, vertical coordinates	



A COMPUTER MODEL OF THE TILTING PAD JOURNAL BEARING SUITABLE FOR THE MICRO-COMPUTER

PART 2: DYNAMIC ANALYSIS

1.0 INTRODUCTION

For many years, it has been known that fluid film journal bearings can cause shaft instability in rotating machinery. This problem has been virtually eliminated with tilting pad journal bearings, and has allowed the maximum operating speed of rotor-bearing systems to be raised significantly. Design of the tilting pad journal bearing is important, but is complicated by the many geometric variables available, such as preload, pivot offset factor, direction of load, number of pads, and bearing clearances.

Prior to any analysis of machine critical speed, stability or unbalance response, accurate data of the dynamic properties of the bearing must be obtained. This report presents stiffness and damping coefficients for the five shoe, tilting pad journal bearing. The five shoe configuration was chosen because of its popularity in industrial machinery. The effect of changing the preload and direction of loading, on the bearing coefficients, is illustrated.

This data is obtained from a computer model of the tilting pad journal bearing, written at the Western Laboratories of the National Research Council of Canada. The program is micro-computer compatible, and provides a full analysis of bearing steady state and dynamic performance. This report also describes the theoretical basis of the computer model.

2.0 BEARING DYNAMICS

Fluid film journal bearings, commonly used in a wide range of rotating machines, play a significant role in the dynamic behaviour of the rotor (Rao, 1983).

The load on the bearing is supported by a thin oil film which separates the moving and stationary surfaces. This oil film acts like a spring and provides damping due to squeeze film effects. These stiffness and damping properties of the oil film significantly alter the critical speeds and out-of-balance response of a rotor (Lund, et al., 1965). Also, the fluid film journal bearing can provide a mechanism for self-excited rotor whirl, which is manifest as an orbiting of the journal, at a subsynchronous frequency close to half of the shaft rotational speed. Such self-excited whirl is usually destructive and is an important factor to be considered in the rotor design.

A journal bearing derives load capacity from viscous pumping of the lubricant through a small clearance space. To generate pressure, the resistance to pumping must increase in the direction of fluid flow. This is accomplished by a radial movement of the shaft, such that the oil film takes the form of the familiar tapered wedge in the direction of motion, as shown in Figure 1.

The static position of the shaft centre with respect to the bearing centre is defined by the eccentricity ratio, ϵ , and the attitude angle, ϕ , such that ϕ goes from approximately 90° to 0° as ϵ goes from zero to one. Thus, the displacement of the journal is not along a line that is co-incident with the load vector. A load in one direction, therefore, causes not only displacement in that direction, but orthogonal displacement as well. Hence, a displacement of the shaft in the bearing clearance space generates a force opposing the displacement, and a force orthogonal to it. Thus, there are strong cross-coupling effects, inherent in a journal bearing, which are significant from the standpoint of its dynamic behaviour.

The cross coupled force system, inherent in a journal bearing, is the basic property that gives rise to the unstable behaviour commonly referred to as half speed whirl. Motion in one direction produces orthogonal forces, which in turn cause orthogonal motion. The process continues and an orbital motion of the shaft results.

Unstable system behaviour is possible when the bearing stiffnesses are such that there exists a natural frequency of vibration of the system at approximately half the running speed.

Several different types of bearings have been developed to meet machine requirements. These have been ranked in approximate order of stability (Garner, et al., 1980). For lightly loaded cases with low stability, the multi-lobe and modified profile bore bearings are used. These work by increasing the load on the bearing. The plain cylindrical bore bearing exhibits strong cross-coupling effects and has proved adequate only for lower speed machines with reasonable bearing loads. For rotors running above their lowest bending critical, the tilting pad journal bearing is used. This type of bearing does not exhibit cross-coupled characteristics and is, therefore, inherently stable.

3.0 SPRING AND DAMPING COEFFICIENTS

The load exerted by the oil film on the rotating shaft varies with both the lateral displacement and velocity of the shaft. The load also varies with acceleration, due to oil inertia effects, but can usually be ignored except in very high speed cases. Tilting of the shaft within the bearing will also produce couples, but it is common to assume that the shaft is aligned with the bearing.

It is convenient to resolve radial and tangential movements and forces into the vertical and horizontal planes. The relationship between incremental forces, displacements and velocities is given by the Equation [1].

$$\begin{array}{ccccccc} A_{xx} & A_{xy} & x & B_{xx} & B_{xy} & \dot{x} & F_x \\ & & + & & & & \\ A_{yx} & A_{yy} & y & B_{yx} & B_{yy} & \dot{y} & F_y \end{array} = \quad (1)$$

where x , y , $\dot{x}$ and $\dot{y}$ are small perturbations about a mean value. The coefficients A and B possess the dimensions of stiffness and damping respectively. Hence, for a give position of the shaft within the bearing clearance space, A is proportional to W/cl and B is proportional to $W/cl/\omega$, where W is the applied load, cl is the bearing radial clearance and ω is the shaft rotational speed (rad/sec).

4.0 COMPUTER MODEL - HANDRUN

4.1 Steady State Analysis

A library program, called HANDRUN, for calculating the steady state performance of the tilting pad journal bearing, was developed at the Western Laboratories of the National Research Council of Canada (Brockwell, et. al., 1986). HANDRUN considers the entire bearing and allows for the inclusion of thermal and elastic distortion of each shoe, variable viscosity, hot oil carry over and turbulence within the oil film.

Oil film pressure is calculated from the Reynolds Equation, ie.:

$$\frac{\delta}{\delta x} \frac{Gxh^3}{\mu} \frac{\delta p}{\delta x} + \frac{\delta}{\delta z} \frac{Gzh^3}{\mu} \frac{\delta p}{\delta z} = \frac{U}{2} \frac{\delta h}{\delta x} + \frac{\delta h}{\delta t} \quad (2)$$

$$\text{where } \frac{1}{Gx} = 12 + 0.0136 \text{ Re}^{0.9} \quad (3)$$

$$\text{and } \frac{1}{Gz} = 12 + 0.0043 \text{ Re}^{0.96} \quad (4)$$

Gx and Gz are turbulence terms (Ng, et al., 1965).

Equation [2] is reduced to a one dimensional form (Ettles, 1980) to reduce computing time. The finite difference form of the equation is solved using the tri-diagonal matrix algorithm.

Film thickness is a function of shaft eccentricity, pad tilt, pad preload, thermal and elastic distortions. Because film thickness is small in relation to the journal radius, changes in film thickness due to these factors may be calculated independently, then summed. Hence:

$$h_{\text{total}} = cl - e \cos(\theta - \psi) - (cl - h_t) - \delta_{\text{preload}} - \delta_{\text{distortion}} \quad (5)$$

Temperature gradients in the bearing, which arise to balance heat generation, convective and conductive heat transfer effects, are calculated from the energy equation.

$$q_x \frac{\delta t}{\delta x} = \frac{a}{\rho C_p} \tau U - q_z \frac{\delta p}{\delta z} - q_x \frac{\delta p}{\delta x} \quad (6)$$

where $q_x = \frac{Gxh^3}{\mu} \frac{\delta p}{\delta x} + \frac{Uh}{2}$ (7)

$$q_z = \frac{-Gzh^3}{\mu} \frac{\delta p}{\delta z} \quad (8)$$

and $\tau = C_f \mu \frac{U}{h} + \frac{h}{2} \frac{\delta p}{\delta x}$ (9)

The turbulent Couette shear stress factor, C_f , is:

$$C_f = 1 + 0.0012 Re^{0.94} \quad (10)$$

It is assumed that: $\frac{\delta T}{\delta z} \ll \frac{\delta T}{\delta x}$

A simple groove mixing theory (Ettles, 1980) is used to account for the carry over of hot oil from one shoe to the next. Upstream pad temperature is given by:

$$T_1 = T_{sup} [1 - \frac{q_0}{q_1}] + T_0 \frac{q_0}{q_1} \quad (11)$$

The model makes no sense when $q_1 = 0$ or when $q_1 < q_0$. Hence, the restriction $.1 \leq q_0/q_1 < .9$ is used.

4.2 Dynamic Analysis

Program HANDRUN has been updated and the eight dynamic coefficients may be calculated for a specified value of shaft eccentricity. The four stiffness coefficients are calculated from a new subroutine entitled STIFF. Subroutine DAMP calculates the four damping coefficients. A listing of the updated program is shown in Appendix A.

Subroutines STIFF and DAMP are both called from the subroutine WHOLE, after HANDRUN has completed the steady state bearing performance calculations. The computational procedure is as follows.

4.2.1 Stiffness coefficients

1. Compute the static values of W and $\dot{\gamma}$ on the static load locus, for the specified value of ϵ .
2. Call subroutine STIFF.

3. Choose small values for incremental displacements (XSTEP = YSTEP = cl/100).
4. With y = 0, calculate PSISTEP and ECCSTEP.
5. Displace shaft -XSTEP and compute the forces TOTXB and TOTYB, for the new shaft location.
6. Displace shaft +XSTEP and compute the forces TOTXF and TOTYF, for the new shaft location.
7. Calculate the two stiffness coefficients Axx, Ayy.
8. With x = 0, calculate PSISTEP and ECCSTEP.
9. Displace shaft -YSTEP and compute TOTXB, TOTYB.
10. Displace shaft +YSTEP and compute TOTXF, TOTYF.
11. Calculate Axy and Ayy.
12. Return to subroutine WHOLE.

The four stiffness coefficients are non-dimensionalized as follows:

$$A_{xx} = A_{xx} \frac{Cl}{W} \text{ etc.} \quad (12)$$

PSISTEP and ECCSTEP are calculated from the following equations, which are derived in Appendix B.

$$\Delta \Psi = (x \cdot \Delta y - y \cdot \Delta x) / (x^2 + y^2) \quad (13)$$

and $\Delta \epsilon = (x \cdot \Delta x + y \cdot \Delta y) / (c^2 \epsilon) \quad (14)$

4.2.2 Damping coefficients

1. Compute W and Ψ for the specified value of ϵ .
2. Call subroutine DAMP.
3. Choose small values for incremental velocities (VXSTEP = VYSTEP = cl. ω /1000).
4. With vy = 0, calculate VPSISTEP and VECCSTEP.
5. Let VECC = -VECCSTEP and VPSI = -VPSISTEP and calculate forces TOTXB, TOTYB.
6. Let VECC = +VECCSTEP and VPSI = +VPSISTEP and calculate forces TOTXF, TOTYF.

7. Calculate damping coefficients B_{xx} , B_{yx} .
8. With $v_x = 0$, calculate $VPSISTEP$ and $VECCSTEP$.
9. Let $VECC = -VECCSTEP$ and $VPSI = -VPSISTEP$ and calculate forces $TOTXB$, $TOTYB$.
10. Let $VECC = +VECCSTEP$ and $VPSI = +VPSISTEP$ and calculate forces $TOTXF$, $TOTYF$.
11. Calculate coefficients B_{xy} , B_{yy} .
12. Return to subroutine `WHOLE`.

The four damping coefficients are non-dimensionalized as follows:

$$B_{xx}' = B_{xx} \frac{(C1.\omega)}{W} \text{ etc.}$$

$VPSISTEP$ and $VECCSTEP$ are calculated from the following

$$\Delta \ddot{y} = (x.\Delta \dot{y} - y.\Delta \dot{x}) / (x^2 + y^2) \quad (15)$$

$$\Delta \dot{\epsilon} = (x.\Delta \dot{x} + y.\Delta \dot{y}) / c^2 \epsilon \quad (16)$$

5.0 DISCUSSION

Steady state results from `HANDRUN`, for tilting pad journal bearings with four, five and eight shoes, have been shown (Brockwell, et al., 1986) to be in good agreement with published data (Boyd, et al., 1953; Lund, et al., 1965; Nicholas, et al., 1978).

5.1 Preload and Bearing Clearances

Nicholas, et al., (1978) present dynamic performance characteristics for the five pad bearing, with varying amounts of preload. The five pad bearing was chosen as it was found to be representative of the most popular type of bearing currently in industrial service.

Preload (or preset) is a term used to describe the relationship between the two clearances found in a tilting pad journal bearing. The "pad radial clearance", C_p , is defined as the difference between the radius of curvature of the pad surface profile and the shaft radius. The second clearance, herein termed the "bearing radial clearance", C_l , is the radial gap between the shaft and the pad, at the pivot position, when the shaft is concentric with the bearing.

Hence, $C_p = R_p - R$

$C_l = R_b - R$

Preload is defined as:

$$m = 1 - \frac{C_l}{C_p} \quad [\text{see Fig. 2}] \quad (17)$$

Jones, et al., (1979) show, diagrammatically, how the two clearances affect the film shapes in the bearing [Fig. 3]. To produce positive preload, the pad clearance must be greater than the bearing clearance, such that the centre of curvature of the pad is not coincident with the geometric centre of the bearing. When the two clearances are equal, the preload is zero. Values of preload in industrial bearings normally range between zero and 0.7 (Jones, et al., 1979).

It is desirable to have all pads in a bearing loaded, since unloaded pads, and even lightly loaded pads, may be unstable and lead to strong sub-synchronous self-excited vibration (Adams, et al., 1983). The usual symptom of this problem is extensive fatigue cracking of the babbitt lining on the unloaded pads, at the upstream (leading edge) region of the pad. Adams, et al., (1983) report noticing this problem in the bearings of large steam turbine generating sets. The condition for all pads to be loaded is purely a function of preload and shaft position. Hence, with very careful design of the bearing, preload values can be selected which ensure that all pads, including those in the top of the bearing, are loaded. Data is given by Jones, et al., (1979) for determining whether or not this condition is satisfied.

5.2 Loading Conditions

Figure 4 shows a five pad bearing with 'on pad' and 'between pads' loading conditions. Industrial bearings are usually found to be operating in a 'between pads' loading condition.

5.3 Program Verification

For this analysis, a bearing with a length to diameter (B/D) ratio of 0.5 and pad arc length of 60° was considered.

Figures 5 and 6 show dimensionless stiffness and damping coefficients vs Sommerfeld Number, for a tilting pad journal bearing with 'on pad' loading and a pivot offset factor of 0.5 (centrally pivoted). These curves show the effect of changing the bearing preload from zero to 0.5. Large increases in the y-direction stiffness are obtained with the preloaded bearing. Increases in y-direction damping are also evident. Large increases in the x-direction stiffness and damping are also obtained with the preloaded bearing, at higher values of the Sommerfeld Number.

Figures 7 and 8 show the effect that a change from an 'on pad' to a 'between pads' loading condition has on the stiffness and damping coefficients. The bearing considered has zero preload and is centrally pivoted. At high Sommerfeld Numbers (low eccentricity ratios), the characteristics of these two bearings approach each other; suggesting that both bearing configurations perform similarly for high speed/low load conditions. For low Sommerfeld Numbers (high eccentricity ratios), there is a significant increase in the x-direction stiffness, for both bearing load configurations. The y-direction stiffness for the 'between pads' conditions also increases with increases in shaft eccentricity. The y-direction stiffness, for the 'on pad' condition, reduces with increases in shaft eccentricity.

The x-direction damping changes less over the range of Sommerfeld Numbers considered. Generally, the y-direction damping decreases with increases in shaft eccentricity. The y-direction damping characteristics of the 'on pad' bearing appears to be particularly poor.

Results presented in Figures 5, 6, 7 and 8 agree reasonably well with those of Nicholas, et al., (1978).

Program HANDRUN confirms that the tilting pad journal bearing does not exhibit cross-coupled spring and damping characteristics.

6.0 CONCLUSIONS

Stiffness and damping coefficients for the five shoe, tilting pad journal bearing have been calculated from a new computer program which is micro-computer compatible. The effect on the bearing coefficients of changing the preload and pad loading are illustrated. Increasing bearing preload increases bearing stiffness and yields stiffness symmetry at low shaft eccentricity ratios. The effect of load direction ('on pad' and 'between pads') appears to make very little difference, at low shaft eccentricity ratios.

The computer program uses a one dimensional form of the Reynolds Equation to reduce computing time, and is written in the FORTRAN language. Bearing dynamic coefficients, calculated from this program, agree reasonably well with other published work.

7.0 FURTHER WORK

Work is in progress to calculate the dynamic coefficients of tilting pad journal bearings, with different geometric designs. This data will be presented in the form of two and three dimensional design charts.

This information will be of assistance to bearing designers, manufacturers and users of rotating machinery.

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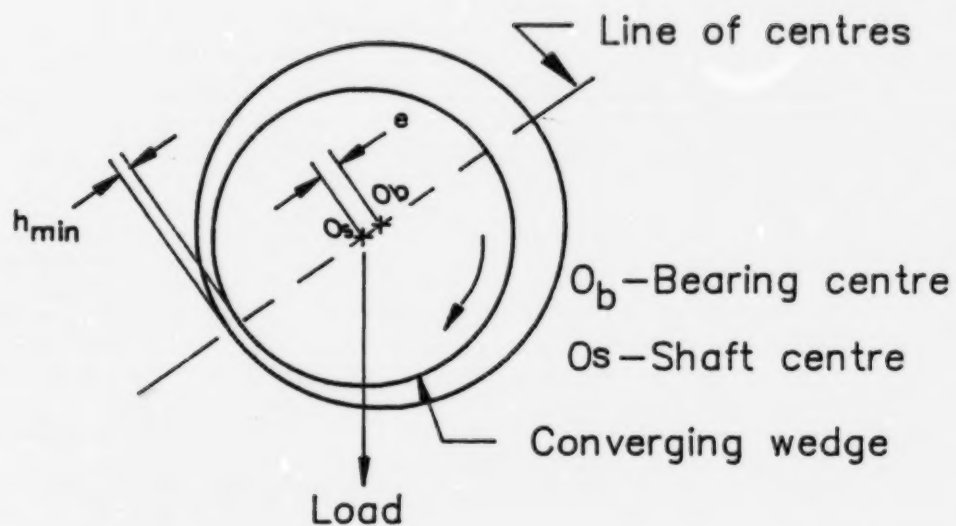


Fig. 1 — Tapered oil film.

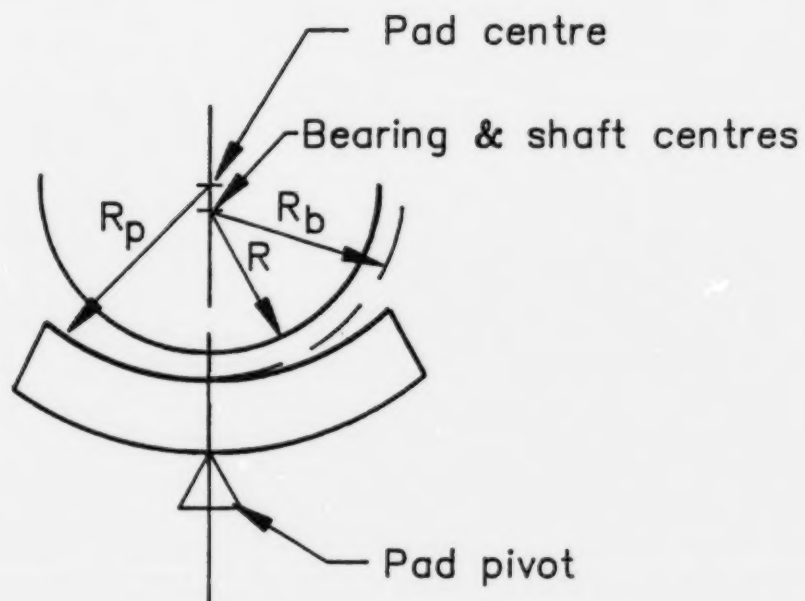


Fig. 2 — Bearing preload.

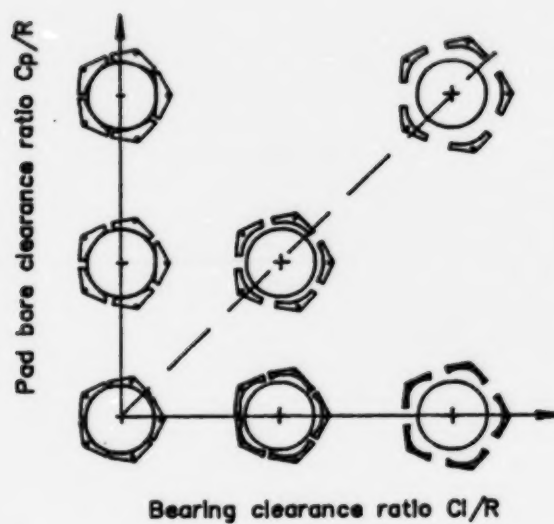


Fig. 3 - Effects of clearances on film shape
(from Jones, et al., 1979)

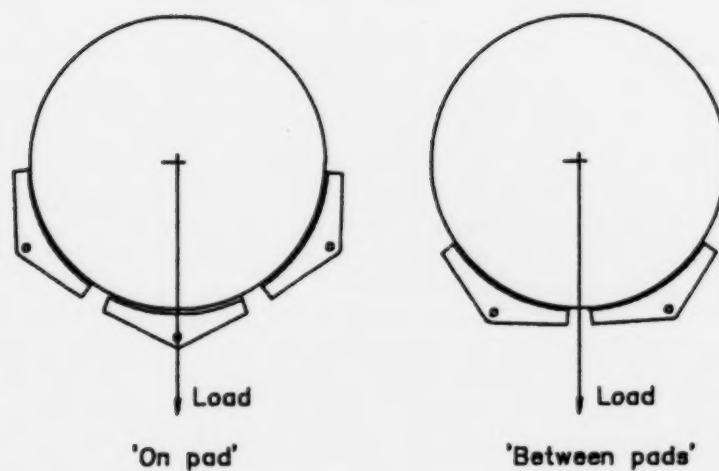


Fig. 4 - 'On pad' and 'between pads' loading conditions.

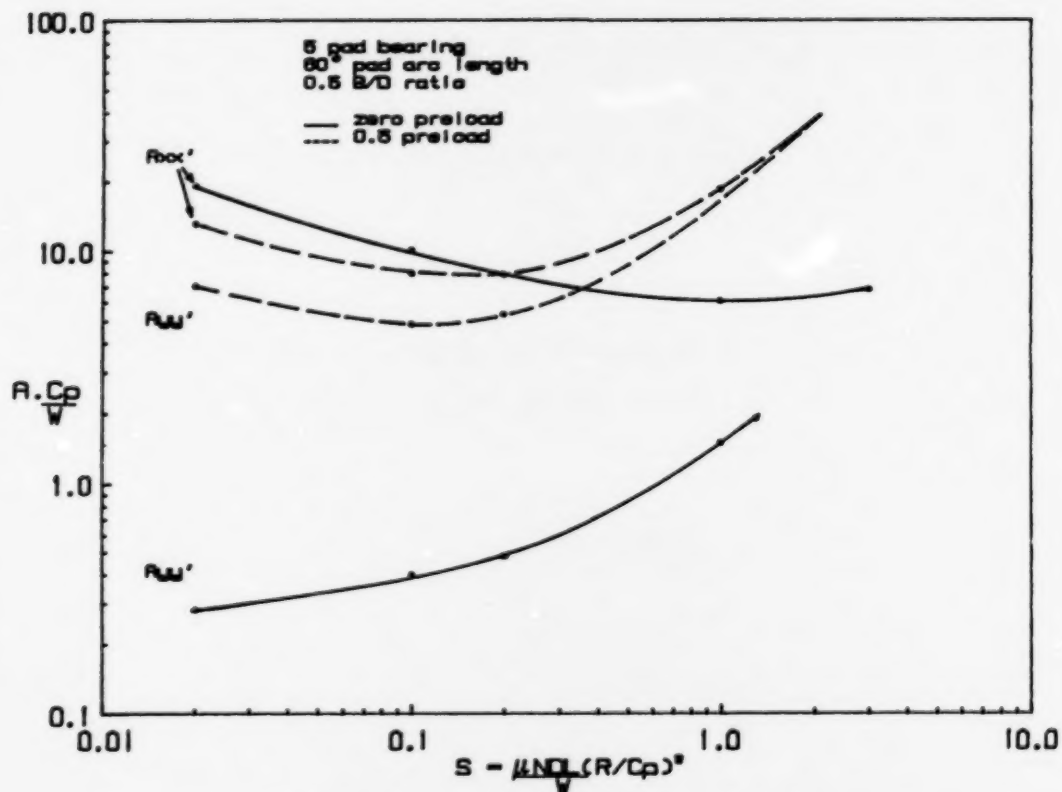


Fig. 5 - Stiffness coefficients for the zero and 0.5 preloaded bearings. Load 'on pad', central pivot.

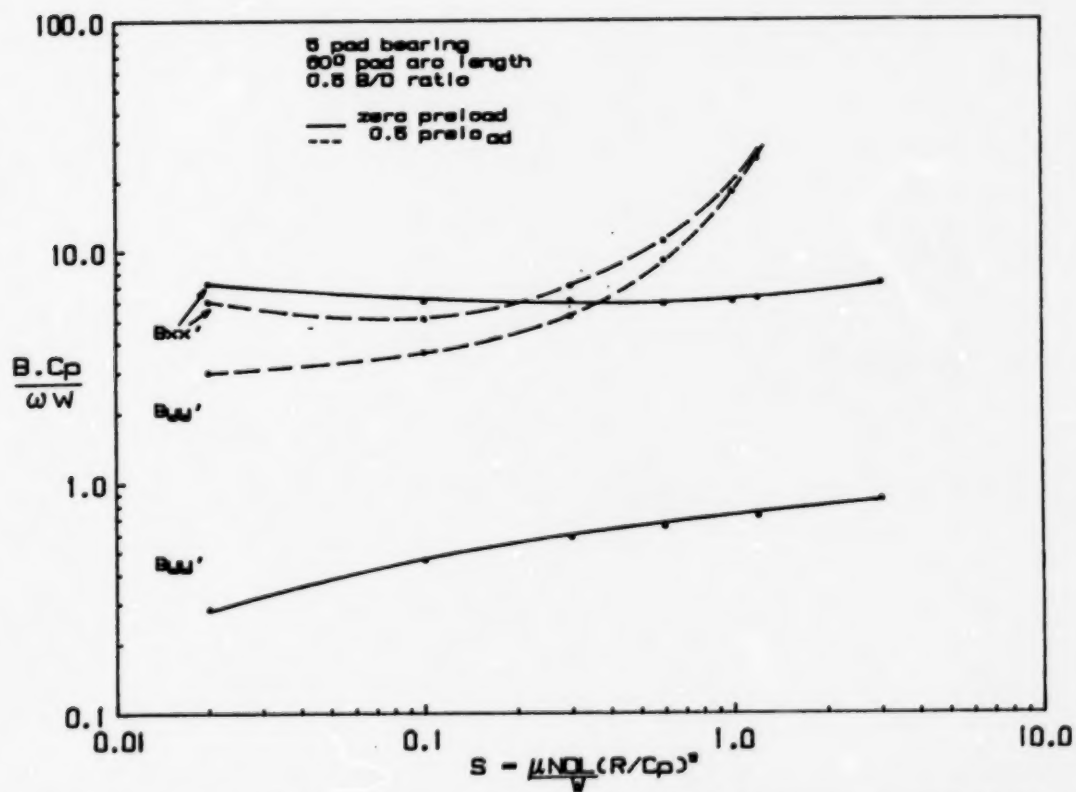


Fig. 8 - Damping coefficients for the zero and 0.5 preloaded bearings. Load 'on pad'. central pivot.

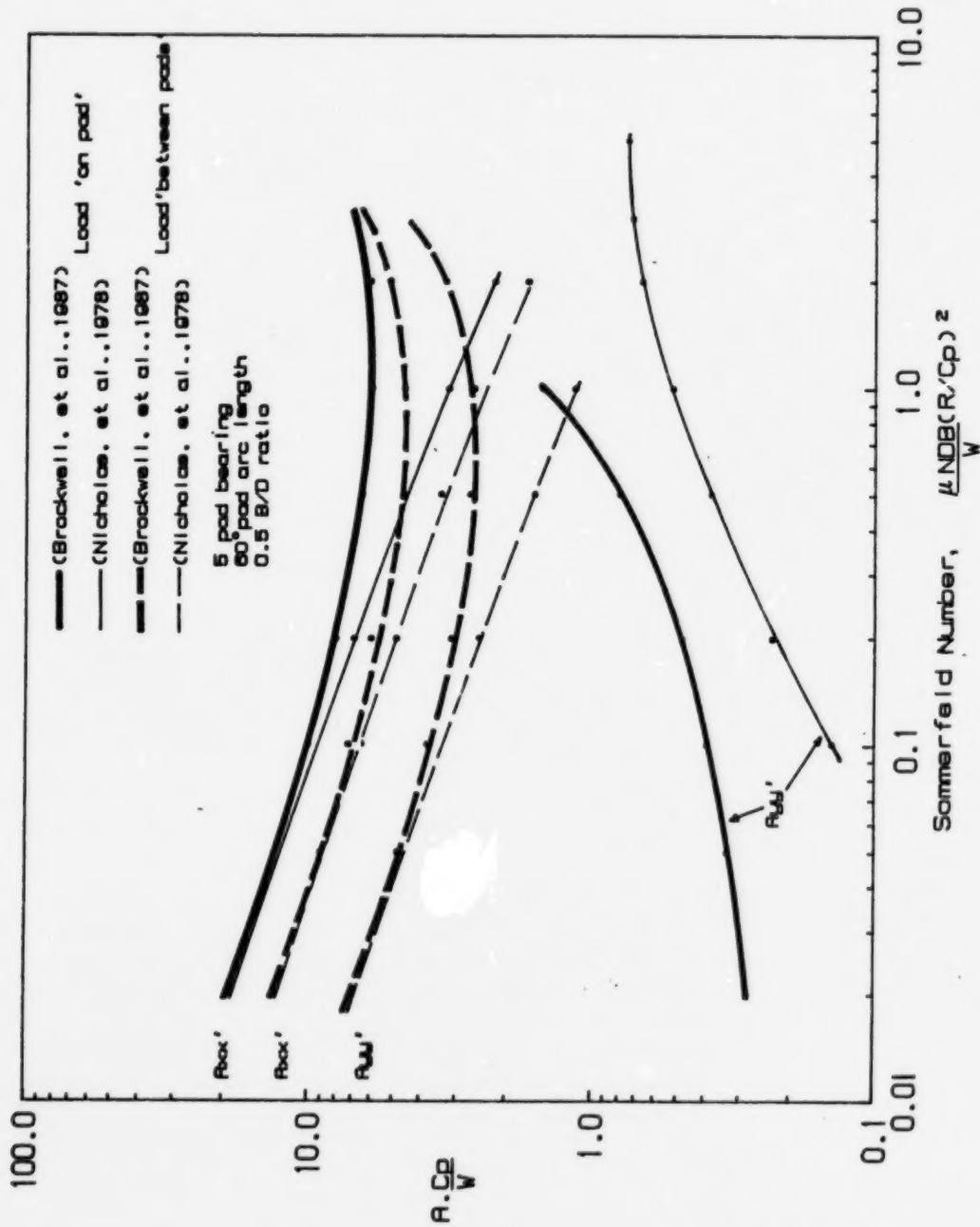


Fig. 7 - Effect of different loading conditions on the stiffness coefficients. Zero preload, central pivot.

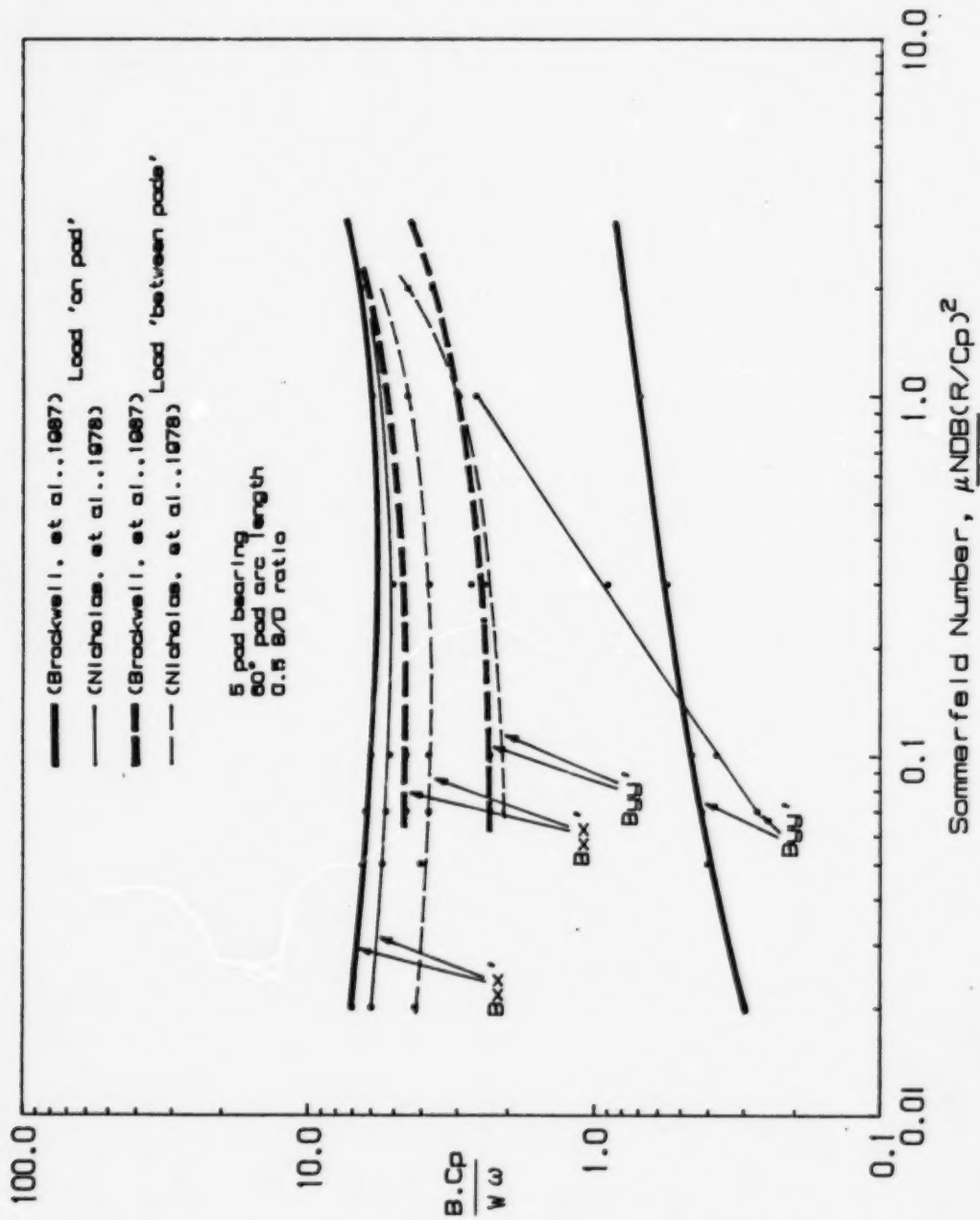


Fig. 8 - Effect of different loading conditions on the damping coefficients. Zero preload, central pivot.

APPENDIX A

Description of Subroutines and Program Listing

Description of Subroutines

Subroutine Name	Description
HANDRUN	Main routine. Accesses subroutines, initializes parameters, contains INPUT-OUTPUT statements, output of user selected variables.
BALANCE	Pad balance routine. Balance is achieved when the moment created by the oil film force goes to zero.
VISFLD	Calculates the viscosity distribution over the pad surface. The VOGEL relationship is used.
GXGZ	Calculates the turbulence factors G_x and G_z and the shear correction factor C_f .
DISTORT	Calculates thermal and elastic deflections of the pad
PRELOAD	Calculates pad shape and stores the information in an array termed SHAPE. SHAPE is empty for a zero preloaded pad.
GEOM	Film thickness and rate of change of film thickness are calculated for all grid points of the specified pad.
FILM	Calculates film pressures from the Reynolds Equation, with turbulence modification, at all grid points. The Reynolds Equation is reduced to a one dimensional form (Ettles, 1980).
HEAT	Calculates the pad temperature distribution, oil flows and bearing power loss.
INTGL	Finds the average pressure at each grid point, then integrates along the pad to find the resultant force. Shear stress is included. Also compares direction of the force with the pivot location.
SUMFORCE	Adds up the forces on each pad
WHOLE	Finds the steady state pad positions and loads for a bearing with given eccentricity, speed, dimensions. Also calls STIFF and DAMP.
OUTPUT	Outputs bearing performance characteristics

APPENDIX A (Cont.)

Subroutine Name	Description
STORAGE	Allows bearing description data to be stored or recalled from user specified files
LTSDAT	Creates a file for the LOTUS 123 data storage routine
COMMON.FOR	Contains REAL, INTEGER, COMMON and DIMENSION statements
STIFF	Calculates the four stiffness coefficients A_{xx} , A_{xy} , A_{yx} , A_{yy}
DAMP	Calculates the four damping coefficients B_{xx} , B_{xy} , B_{yx} , B_{yy}

```
C*****
C                                     HANDRUN                                     *
C*****
C                                     APRIL 28,1986
C The subroutines accessed by this program are:
C   BALANCE,VISFLD,GXGZ,DISTORT,PRELOAD,GEOM,FILM,HEAT
C   INTGL(filename:INTLT),SUMFORCE(filename:FORCES),
C   WHOLE,OUTPUT,STORAGE,STIFF,DAMP,LTS DAT
C
C HANDRUN is organized into 4 main sections:
C   Initialization of parameters.
C   Input-output statements for the input of bearing descriptions,
C   program options, and data for subroutine debugging.
C   Calling statements for the subroutines, including the
C   subroutine WHOLE which itself calls all the subroutines
C   necessary to analyse the bearing.
C   Output of user selected variables.
C
C***** PRELIMINARY INITIALIZATION *****
C   INTEGER I,J
C   REAL DTHT,DTEMP,POW
C
C   REAL PHI ,VPHI, TEMPO,THT,P,PP,PS
C   DIMENSION PS(20,8),PP(20,20),POW(8)
C   DIMENSION P(20,8)
C $INCLUDE:'COMMON.FOR'
C Open a file for LOTUS 123 data storage. Data will be stored in
C the file every time the subroutine LTS DAT is called.
C   OPEN(7,FILE='LTS DAT.PRN',STATUS='NEW')
C
C   WRITE(*, '(A)') ' ENTER CURRENT DATE AND USER NAME
C   READ(*, '(A70)') DATE
C   WRITE(4, '(A70)') DATE
C SET CONSTANTS FOR BEARING TYPE AND GRID FINENESS
C   PI=3.141592654
C   M=19
C   ITTRT=3
C { DEFAULT NO. OF ITERATIONS=3}
C   IOFLAG=1
C { DEFAULT IS MINIMUM OUTPUT}
C   HFLAG=3
C { DEFAULT IS EMPIRICAL MARTIN HEAT BALANCE}
C   E=200000000000.
C {Young's mod. for steel is 200 GPa}
C   G=80000000000.
C {Shear mod. is 80 GPa}
C   ALF=.000012
C {Coef. of thermal expansion is 1.2E-5 strain/deg.C}
```

```

DO 50 I=1,M+1
    SHAPE(I)=0.0
DO 40 J=1,8
    GX(I,J)=1/12.0
    GZ(I,J)=1/12.0
    CF(I,J)=1.0
    T(I,J)=350.
    P(I,J)=0.0
    DSTRT(I,J)=0.0
    VISC(I,J)=.01
    THTO(J)=0
    PHIO(J)=0
    VPHIO(J)=0
    POWER(J)=0
    QLAST(J)=0
    QIN(J)=0
    FX(J)=0
    FY(J)=0
    DSTRT(I,J)=0
    H(I,J)=0
    VH(I,J)=0
40     CONTINUE
50     CONTINUE
    TYPE=1
C These variables are initialized arbitrarily to make certain 'divide
C by zero' errors unlikely.
C The conditions above are: laminar flow in a bearing at temperature
C =350 K, no load, no distortions, no preload, .01 Pa-s viscosity.

C The first time through, control is transferred directly to INITIAL.
    GOTO 1000

100    CONTINUE
C At this point, the program has just returned from the
C initialization, calling or outputting routine, so that
C some variables may have new values. Therefore, variables
C depending on these potentially changed values must be
C recalculated.
    U=W*R
    THICK=BP
    DX=R*(THTL+THTT)/M
C U=shaft surface speed; THICK=pad thickness (approx-
C imated by the distance from the pad surface to the
C pad pivot); DX=the grid spacing; R=shaft radius;
C THTL,THTT=angular extents of pad before and after
C the pivot; M=no. of grid points=19; W=rad/s of shaft.

C
C MAIN MENU

CC NOW THE CHOICES ARE:1) MORE INITIALIZATION
C C 2) CALL SUBROUTINES
C C 3) OUTPUT OF DATA
C C 4) STOP

C PAUSE TO ALLOW USER TO TURN PrtSc OFF
    READ(*,'(F12.6)') DUMMY

```

C OUTPUT CHOICES:

WRITE(*, '(A)') ' 1)initialize 2)call 3)output 4)stop'

READ(*, '(I3)') K

GOTO (1000,2000,3000,4000) K

GO TO 100

C INITIALIZATION ROUTINE

1000 CONTINUE

C This routine allows the user to input variables from selected
C classes. The control variable is L.

C INITIALIZATION MENU

WRITE(*, '(A)') ' INITIALIZATION MENU:'

WRITE(*, '(A)') ' 1--->P'

WRITE(*, '(A)') ' 2--->T'

WRITE(*, '(A)') ' 3--->GX'

WRITE(*, '(A)') ' 4--->GZ'

WRITE(*, '(A)') ' 5--->CF'

WRITE(*, '(A)') ' 6--->VISC'

WRITE(*, '(A)') ' 7--->bearing description'

WRITE(*, '(A)') ' 8--->E,G,alfa'

WRITE(*, '(A)') ' 9--->DEFAULT BEARING'

WRITE(*, '(A)') ' 10-->PROGRAM OPTIONS'

READ(*, '(I3)') L

GOTO (1010,1020,1030,1040,1050,1060,1700, 1800,1900,1950) L

GOTO 100

C (if L>7, bypass initialization routine)

C Pressure Initialization (used debugging the program)

1010 WRITE(*, '(A)') ' P=A*I + B'

WRITE(*, '(A)') ' A='

READ(*, '(F15.5)') A

WRITE(*, '(A)') ' B='

READ(*, '(F18.6)') B

DO 1018 J=1,TYPE

DO 1014 I=1,M+1

P(I,J)=A*I+B

1014 CONTINUE

1018 CONTINUE

GO TO 100

C (this returns control to the main menu)

C Temperature Initialization (for debugging)

1020 WRITE(*, '(A)') ' T=A*I + B'

WRITE(*, '(A)') ' A='

READ(*, '(F15.5)') A

WRITE(*, '(A)') ' B='

READ(*, '(F18.6)') B

DO 1028 J=1,TYPE

DO 1024 I=1,M+1

T(I,J)=A*I+B

1024 CONTINUE

1028 CONTINUE

GO TO 100

c Tubulence factor GX initialization (for debugging)

```
1030  WRITE(*,'(A)') ' GX=A*I + B'
      WRITE(*,'(A\)' ) ' A='
      READ(*,'(F15.5)') A
      WRITE(*,'(A\)' ) ' B='
      READ(*,'(F18.6)') B
      DO 1038 J=1,TYPE
        DO 1034 I=1,M+1
          GX(I,J)=A*I+B
1034    CONTINUE
1038  CONTINUE
      GO TO 100
```

c GZ initialization

```
1040  WRITE(*,'(A)') ' GZ=A*I + B'
      WRITE(*,'(A\)' ) ' A='
      READ(*,'(F15.5)') A
      WRITE(*,'(A\)' ) ' B='
      READ(*,'(F18.6)') B
      DO 1048 J=1,TYPE
        DO 1044 I=1,M+1
          GZ(I,J)=A*I+B
1044    CONTINUE
1048  CONTINUE
      GO TO 100
```

c CF (turbulent shear stress factor)

```
1050  WRITE(*,'(A)') ' CF=A*I + B'
      WRITE(*,'(A\)' ) ' A='
      READ(*,'(F15.5)') A
      WRITE(*,'(A\)' ) ' B='
      READ(*,'(F12.7)') B
      DO 1058 J=1,TYPE
        DO 1054 I=1,M+1
          CF(I,J)=A*I+B
1054    CONTINUE
1058  CONTINUE
      GO TO 100
```

c Viscosity initialization

```
1060  WRITE(*,'(A)') ' VISC=A*I + B'
      WRITE(*,'(A\)' ) ' A='
      READ(*,'(F15.5)') A
      WRITE(*,'(A\)' ) ' B='
      READ(*,'(F12.6)') B
      DO 1068 J=1,TYPE
        DO 1064 I=1,M+1
          VISC(I,J)=A*I+B
1064    CONTINUE
1068  CONTINUE
      GO TO 100
```

c This is the main display formatting for bearing description.

```

1700  CONTINUE
      WRITE(*, '( /A)') ' 1. ANGULAR GEOMETRY'
      WRITE(*, '(A,I3)') ' NO. OF PADS :', TYPE
      WRITE(*, '(A,2F12.3)') ' LEADING, TRAILING EXTENT:', THTL, THTT
      DO 1710 J=1, TYPE
        WRITE(*, '(A,I3,A,F12.4)') ' J=', J, ' THTO=', THTO(J)
1710  CONTINUE

      WRITE(*, '( /A)') ' 2. SIZE'
      WRITE(*, '(7X,A,13X,A,13X,A,13X,A,10X,A)') ' R', 'BR', 'CL', 'BP',
C      'PRELOAD'
      WRITE(*, '(F12.8,3F15.8,F15.8)') R, BR, CL, BP, PRLD

      WRITE(*, '( /A)') ' 3. OIL'
      WRITE(*, '(3X,A,7X,A,7X,A,7X,A,12X,A,8X,A,8X,A)') 'VISO',
C      'TO', 'VIS1', 'T1', 'RO', 'CP', 'TSUP'
      WRITE(*, '(4F10.5,3F11.4)') VISO, TO, VIS1, T1, RO, CP, TSUP

      WRITE(*, '( /A)') ' 4. INITIAL RUNNING CONDITIONS'
      WRITE(*, '(7X,A,13X,A,12X,A,11X,A,12X,A)') 'W', 'ECC', 'VECC',
C      'PSI', 'VPSI'
      WRITE(*, '(F10.3,4F15.8)') W, ECC, VECC, PSI, VPSI

      WRITE(*, '( /A)') ' 5. OTHER PARAMETERS'
      WRITE(*, '(3X,A,6X,A,8X,A,10X,A,8X,A)') 'GRID SIZE',
C      'TOLTLT', 'TTOL', 'NE', 'ABSRB'
      WRITE(*, '(I8,4X,4F13.7)') M, TOLTLT, TTOL, NE, ABSRB

      WRITE(*, '(A)') ' CHOOSE WINDOW TO CHANGE (1-6, 6=NO WINDOW)'
      READ(*, '(I3)') K
      GO TO (1720, 1720, 1730, 1740, 1750) K
      GOTO 100

1720  CONTINUE
c Now input angular geometry data. (pad location, extent)
      WRITE(*, '( /A)') ' # OF PADS='
      READ(*, '(I6)') TYPE
      WRITE(*, '(A)') ' PAD POSITIONS? (RADIANs)'
      DO 1723 J=1, TYPE
        READ(*, '(F12.8)') THTO(J)
1723  CONTINUE
      WRITE(*, '(A)') ' THTT='
      READ(*, '(F12.8)') THTT
      WRITE(*, '(A)') ' THTL='
      READ(*, '(F12.8)') THTL

c Now, input radius, breadth, clearance, pad thickness
      WRITE(*, '( /A)') ' RADIUS='
      READ(*, '(F12.8)') R
      WRITE(*, '(A)') ' BREADTH='
      READ(*, '(F12.8)') BR
      WRITE(*, '(A)') ' CLEARANCE='
      READ(*, '(F12.8)') CL
      WRITE(*, '(A)') ' PIVOT DIST. (THICK)= '
      READ(*, '(F12.8)') BP
      WRITE(*, '( /A)') ' PRELOAD='
      READ(*, '(F10.7)') PRLD
      GOTO 100
1730  CONTINUE

```

```

1800  WRITE(*,'(A)') ' Pad Distortion Parameters:'
      WRITE(*,'(A)') ' Young's mod.(GPa)='
      READ(*,'(F8.2)') E
      E=E*1000000000.
C      {this converts GPa to Pa: the program uses S.I.}
      WRITE(*,'(A)') ' Shear mod.(GPa) ='
      READ(*,'(F8.2)') G
      G=G*1000000000.
C      { GPa -->Pa }
      WRITE(*,'(A)') ' coef. of thermal expansion (*E-5)'
      READ(*,'(F12.5)') ALF
      ALF=ALF*.00001
C      {ALF --> strain/degree C }

      GOTO 100
1900  CALL STORAGE
c      STORAGE transfers a bearing description to and from
c      a user-named file on the current directory.
      GOTO 100
1950  CONTINUE
      WRITE(*,'(A)') ' NO. OF VISC-TEMP.-DISTORT-LOAD ITERATIONS'
      READ(*,'(I3)') ITTRT
      WRITE(*,'(A)') ' SELECT HEAT BALANCE METHOD:'
      WRITE(*,'(A)') ' 1-->ETTLES FINITE DIF. MARCHING'
      WRITE(*,'(A)') ' 2-->POWER FROM OIL SHEAR; TEMP. AS BY MARTIN'
      WRITE(*,'(A)') ' 3-->EMPIRICAL POWER; TEMP. AS BY MARTIN'
      READ(*,'(I3)') HFLAG
      WRITE(*,'(A)') ' OUTPUT OPTIONS'
      WRITE(*,'(A)') ' 1-->NO PRESSURE,FILM PROFILES ETC.'
      WRITE(*,'(A)') ' 2-->ROUGH PRESSURE, ETC PROFILES'
      WRITE(*,'(A)') ' 3-->FULL OUTPUT'
      READ(*,'(I3)') IOFLAG

      GOTO 100

C CALLING MENU:
2000  CONTINUE
      WRITE(*,'(A)') ' 1---> VISFLD'
      WRITE(*,'(A)') ' 2---> GEOM'
      WRITE(*,'(A)') ' 3---> FILM,INTGL'
      WRITE(*,'(A)') ' 4---> INTGL'
      WRITE(*,'(A)') ' 5---> HEAT'
      WRITE(*,'(A)') ' 6---> GXGZ'
      WRITE(*,'(A)') ' 7--> PAD BALANCE'
      WRITE(*,'(A)') ' 8--> PRELOAD'
      WRITE(*,'(A)') ' 9-> DISTORT'
      WRITE(*,'(A)') ' 10-> WHOLE BEARING ANALYSIS'
      READ(*,'(I3)') L
      GOTO (2010,2020,2030,2030,2052,2060,2080,2090
C      ,2200,2300) L
      GO TO 100

2010  CALL VISFLD
      GOTO 100

```

```

c Input oil description data.
  WRITE(*, '( /A\ )' ) ' OIL SUPPLY TEMP.= '
  READ(*, '(F8.3)' ) TSUP

  WRITE(*, '( /A\ )' ) ' OIL DENSITY= '
  READ(*, '(F9.5)' ) RO
  WRITE(*, '(A\)' ) ' SPECIFIC HEAT= '
  READ(*, '(F9.5)' ) CP

  WRITE(*, '( /A\ )' ) ' VISO= '
  READ(*, '(F8.6)' ) VISO

  WRITE(*, '(A\)' ) ' TO= '
  READ(*, '(F10.4)' ) TO

  WRITE(*, '(A\)' ) ' VIS1= '
  READ(*, '(F8.6)' ) VIS1

  WRITE(*, '(A\)' ) ' T1= '
  READ(*, '(F10.4)' ) T1
  GOTO 100
1740 CONTINUE
c Input running conditions: shaft, pad positions, and speed.
  WRITE(*, '(A\)' ) ' W(rad/s)= '
  READ(*, '(F10.4)' ) W

  WRITE(*, '( /A\ )' ) ' ECC= '
  READ(*, '(F8.7)' ) ECC

  WRITE(*, '(A\)' ) ' dECC/dt= '
  READ(*, '(F9.6)' ) VECC

  WRITE(*, '(A\)' ) ' PSI= '
  READ(*, '(F9.6)' ) PSI

  WRITE(*, '(A\)' ) ' dPSI/dt= '
  READ(*, '(F10.6)' ) VPSI

  GOTO 100
1750 CONTINUE
c Input miscellaneous data.
  WRITE(*, '( /A\ )' ) ' ANGULAR TILT TOLERANCE= '
  READ(*, '(F12.8)' ) TOLTLT
  TOLTLT= allowable moment about the pad pivot.
c
  WRITE(*, '(A\)' ) ' TEMP. TOLERANCE= '
  READ(*, '(F12.8)' ) TTOL
  WRITE(*, '(A\)' ) ' SCHELLY EXPN.= '
  READ(*, '(F12.8)' ) NE
  IF (NE.EQ.0.0) NE=2.0+ .51/((THTT+THTL)*R/BR)**1.66
c If NE is not specified, it is given a reasonable value.
  WRITE(*, '(A\)' ) ' ABSORPTION CONSTANT= '
  READ(*, '(F12.8)' ) ABSRB
c
  ABSRB=fraction of generated heat absorbed by oil.
  GOTO 100

```

```

3010    CONTINUE
c This is the main display formatting for bearing description.
      WRITE(4, '(//A)') ' 1. ANGULAR GEOMETRY'
      WRITE(4, '(A,I3)') ' NO. OF PADS :', TYPE
      WRITE(4, '(A,2F12.3)') ' LEADING, TRAILING EXTENT:', THTL, THTT
      DO 3020 J=1, TYPE
        WRITE(4, '(A,I3,A,F12.4)') ' J=', J, ' THTO=', THTO(J)
3020    CONTINUE

      WRITE(4, '(//A)') ' 2. SIZE'
      WRITE(4, '(7X,A,13X,A,13X,A,13X,A,10X,A)') ' R', 'BR', 'CL', 'BP',
c 'PRELOAD'
      WRITE(4, '(F12.8,3F15.8,F15.8)') R, BR, CL, BP, PRLD

      WRITE(4, '(//A)') ' 3. OIL'
      WRITE(4, '(3X,A,7X,A,7X,A,7X,A,12X,A,8X,A,8X,A)') ' VISO',
c 'TO', 'VIS1', 'T1', 'RO', 'CP', 'TSUP'
      WRITE(4, '(4F10.5,3F11.4)') VISO, TO, VIS1, T1, RO, CP, TSUP

      WRITE(4, '(//A)') ' 4. INITIAL RUNNING CONDITIONS'
      WRITE(4, '(7X,A,13X,A,12X,A,11X,A,12X,A)') ' W', 'ECC', 'VECC',
c 'PSI', 'VPSI'
      WRITE(4, '(F10.3,4F15.8)') W, ECC, VECC, PSI, VPSI

      WRITE(4, '(//A)') ' 5. OTHER PARAMETERS'
      WRITE(4, '(3X,A,6X,A,8X,A,10X,A,8X,A)') ' GRID SIZE',
c 'TOLTLT', 'TTOL', 'NE', 'ABSRB'
      WRITE(4, '(I8,4X,4F13.7)') M, TOLTLT, TTOL, NE, ABSRB

3060    WRITE(4, '(A,F10.6,A,F10.6)') ' DX=', DX, ' U=', U
      WRITE(4, '(A)') ' '
      WRITE(4, '(A,F8.2)') ' ELASTIC MODULAS (GPa) =', E/10000000000.
      WRITE(4, '(A,F8.2)') ' SHEAR MODULAS (GPa) =', G/10000000000.
      WRITE(4, '(A,F8.3)') ' STRAIN/DEG. C (*E5) =', ALF*100000.
      IF(HFLAG.EQ.1) WRITE(4, '(A)') ' ETTLES HEAT BAL.'
      IF(HFLAG.EQ.2) WRITE(4, '(A)') ' SH. STRSS POW.; MARTIN BAL.'
      IF(HFLAG.EQ.3) WRITE(4, '(A)') ' EMP'CL POW.; MARTIN BAL.'
      GOTO 100

3070    CONTINUE
      WRITE(*, '(A\)\') ' J='
      READ(*, '(I3)') J
      WRITE(*, '(A,I3/A)') ' SCRAPE=', SCRAPE,
c ' THT H VH SHAPE'

      DO 3074 I=1, M+1
        THT=THTO(J)-THTL+DX/R*(I-1)
3074    WRITE(*, '(4F11.7)') THT, H(I,J), VH(I,J), SHAPE(I)
      CONTINUE

      GOTO 100

3080    CONTINUE
      WRITE(*, '(A\)\') ' J='
      READ(*, '(I3)') J
      WRITE(*, '(A)') ' '
c ' THT H VISC GX
c GZ CF'
      DO 3084 I=1, M+1
        THT=THTO(J)-THTL+DX/R*(I-1)
        THT=THT*57.29
      WRITE(*, '(6E13.5)') THT, H(I,J), VISC(I,J), GX(I,J), GZ(I,J)
c ,CF(I,J)
3084    CONTINUE

```

- All -

```
2020  WRITE(*,'(A)') ' PAD#='
      READ(*,'(I3)') J
      PHI=PHIO(J)
C for this model, pad velocity is neglected.
      VPHI=0.0
      CALL GEOM(J,PHI,VPHI)
      GOTO 100

2030  WRITE(*,'(A)') ' PAD#='
      READ(*,'(I3)') J
      CALL FILM(J,P)
      CALL INTGL(J,P,DTHT)
      WRITE(*,'(A)') ' FILM,INTGL were run.'
      GOTO 100

2052  CONTINUE
      CALL HEAT(P)
      CALL SUMFORCE
      GOTO 100

2060  CONTINUE
      CALL GXGZ
      GOTO 100

2080  CONTINUE
      WRITE(*,'(A)') ' J='
      READ(*,'(I3)') J
      CALL BALANCE(J,P)
      GOTO 100

2090  CONTINUE
      CALL PRELOAD(PRLD)
      GOTO 100

2200  WRITE(*,'(A)') ' J='
      READ(*,'(I3)') J
      CALL DISTORT(J,P)
      GOTO 100

2300  CALL WHOLE(P,PRLD)
      GOTO 100

C      OUTPUT ROUTINE
3000  CONTINUE
      WRITE(*,'(A)') '
      WRITE(*,'(A)') ' 1
      WRITE(*,'(A)') ' 2
      WRITE(*,'(A)') ' 3
      WRITE(*,'(A)') ' 4
      WRITE(*,'(A)') ' 5
      WRITE(*,'(A)') ' 6
      WRITE(*,'(A)') ' 7
      OUTPUT MENU'
      bearing description'
      THT,H,VH,SHAPE,SCRAPE'
      VISC,GX,GZ,CF'
      T,P,POWER,QLAST,QIN,DTEMP'
      FX,FY,DTHT for P when INTGL called'
      P'
      DSTRT,TENS,SHEAR,BENDM'

      READ(*,'(I3)') L
      GOTO (3010,3070,3080,3090,3100,3110,3130) L

      GO TO 100
```

```

GOTO 100

3090  WRITE(*,'(A)\') ' J='
      READ(*,'(I3)') J
      WRITE(*,'(A)\') '          T          P '
      DO 3094 I=1,M+1
        WRITE(*,'(2F15.2)') T(I,J),P(I,J)
3094  CONTINUE
      WRITE(*,'(A,F10.3,A,2F12.8//)') ' POWER=',POWER(J),
C    ' Qin,Qout=',QIN(J),QLAST(J)
      WRITE(*,'(A,F6.1)') ' very approx. T rise=', DTEMP
      WRITE(*,'(A,F7.2)') ' approx. power=',POW(J)
3098  CONTINUE
      GOTO 100

3100  WRITE(*,'(A)\') ' J='
      READ(*,'(I3)') J
      WRITE(*,'(A,F15.5,A,F15.5,A,F15.9)') ' FX',FX(J),' FY',FY(J)
C    ' DTHT=',DTHT
      WRITE(*,'(A,F12.3)') ' hi/ho=',H(1,J)/H(20,J)
      WRITE(*,'(A,F16.2)') ' MOMENT=',-DTHT*R*(FX(J)**2+FY(J)**2)**
      WRITE(*,'(A,I3)\') ' pad#',J
      GOTO 100
3110  CONTINUE

      WRITE(*,'(A)\') ' DIMENSIONLESS? P=P/(VIS*W*(R/CJ^2) .1=YES'
      READ(*,'(I2)') K
      CNVRT=1.0
      IF(K.EQ.1) CNVRT=1.0/(VIS0*W*(R/CL)**2)
C  If desired, it is possible to output P in a non-dimensional
C  form.
      WRITE(*,'(A)\') '          P          J='
      READ(*,'(I3)') J
      DO 3118 I=1,M+1
        WRITE(*,'(F12.1)') P(I,J)*CNVRT
3118  CONTINUE
      GOTO 100

3130  WRITE(*,'(A)\') ' J='
      READ(*,'(I3)') J
      WRITE(*,'(A)\') ' I          DISTORT          TENS , SHEAR, BENDM'
      DO 3135 I=1,20
        WRITE(*,'(I4,4F15.8)') I,DSTRT(I,J),TENS(I),SHEAR(I),BENDM(I)
3135  CONTINUE
      GOTO 100

C Close the LOTUS file:
      CLOSE(7)
4000  STOP
      END

```

```

C-----
C      SUBROUTINE BALANCE(J,P)
C      MARCH 13,1986
C-----
C      REAL PHI, DPHI, MOM,MOM1,FMAG,DTHT,DTHT1,VPHI,DM
C      REAL P, DAMPER
C      INTEGER J,COUNT
C      DIMENSION P(20,8)

$INCLUDE: 'COMMON.FOR'
C THE ROUTINE SEARCHS FOR THE PHI WITH MINIMUM MOMENT ABOUT PIVOT.
C PHI0(J) is the current value of tilt for pad j : it is the starting
C point for the balancing routine. DPHI is the correction in the
C pad tilt; it is computed by comparing the pivot moments for the last
C 2 tilts. DPHI is arbitrarily initialized to get the routine moving.

C DAMPER is used to slow down the 'oscillations' of an unstable pad.
C As it becomes apparent that the pad is not converging, damper
C increases, and the amplitude DPHI of the oscillations is decreased
C proportionally.

C COUNT is the number of iterations performed. When COUNT is large
C it is assumed that the pad will not balance.

C FIRST: give the routine a starting point.
      COUNT=0
      VPHI=0.0
C A reasonable guess to make is that hi/ho=2.0.
C HPO -pad outlet film thickness with phi=0
C HPI -"" inlet "" "" "" "" ""
C DNOM - a linear combination of dh/dphi 's at inlet and outlet
      HPO=CL*(1-ECC*COS(THTO(J)+THTT-PSI))-SHAPE(20)-DSTRT(20,J)
      HPI=CL*(1-ECC*COS(THTO(J)-THTL-PSI))-SHAPE(1)-DSTRT(1,J)
      DNOM=(R+BP)*(2*SIN(THTT)+SIN(THTL))
      PHI0(J)=(2*HPO-HPI)/DNOM

      DAMPER=1.0
      PHI=PHI0(J)
      DPHI=0.0001
C      {this initial DPHI seems to work; any small value should
C      work}
      CALL GEOM(J,PHI,VPHI)
      CALL FILM(J,P)
      CALL INTGL(J,P,DTHT)
      FMAG=SQRT(FX(J)**2+FY(J)**2)
      MOM=DTHT*FMAG
C      The moment about the pivot is Force*Arm; in this case
C      the force is the film force resultant FMAG acting at
C      an arm of DTHT*R. Since R is constant for the bearing,
C      the routine works with DTHT alone ie, MOM is moment
C      per unit radius.
      IF(IOFLAG.EQ.3)WRITE(*,400) ' PHI0 rad', 'PHI1', 'MOM N-m', 'MOM1

C SECOND: make next guess for tilt or exit routine.
C      Stop routine when either a) moment for PHI0(j) is small
C      or b) tilt correction is small

```

```

c                                     or                c) the pad is unstable.
100      CONTINUE
c      {routine returns from each iteration to this point}
      IF (ABS(MOM).LT.TOLTLT*COUNT) GO TO 200
      IF (ABS(DPHI).LT..000000000001) GOTO 150
c At this point, another guess is needed.
      PHI1=PHIO(J)+DPHI
      CALL GEOM(J,PHI1,VPHI)
c It is possible that PHI1 is an unreasonable guess. Therefore, check
c to make sure the pad is not scraping.
      IF (SCRAPE.GT.0) THEN
          DPHI=DPHI/2
          DAMPER=DAMPER*1.1
          GOTO 100
c      { go back to make a new guess}
      ELSE
c      {PHI1 okay; calculate the moment at phi=PHI1, new DPHI.
          CALL FILM(J,P)
          CALL INTGL(J,P,DTHT1)
          FMAG1=SQRT(FX(J)**2+FY(J)**2)
          MOM1=DTHT1*FMAG1
          DM=MOM-MOM1
          IF (ABS(DM).LT.TOLTLT) DM=DM/ABS(DM)*DAMPER*TOLTLT
          DPHI=DPHI *MOM1/DM/DAMPER
          END IF

c It is assumed that PHI1 is a better estimate of tilt than PHIO.
c Therefore, set PHIO to PHI1 and start over.
          IF (IOFLAG.EQ.3) WRITE(*,450) PHIO(J),PHI1,MOM,MOM1

          PHIO(J)=PHI1
          MOM=MOM1
          COUNT=COUNT+1
          IF (COUNT.LT.40) GOTO 100
150      CONTINUE
          FX(J)=0.0
          FY(J)=0.0
c If the pad is unbalanced, set loads to 0.0
c This reduces "noise" for the bearing coefficient calculations
c If the pad has not balanced in 40 iterations, it will probably
c never balance stably.
c
200      CONTINUE

400      FORMAT(A,10X,A,10X,A,10X,A)
450      FORMAT(4F16.10)

      RETURN
      END

```

```

C-----
C      SUBROUTINE VISFLD
C      MARCH 14, 1985
C Given the temperature array T, VISFLD calculates the viscosities
C for the points between the temperatures (ie. T and VISC contain
C information about points that are staggered.)

C To calculate viscosities, VISFLD must have two reference points :
C                                     TO,VISO; T1,VIS1
C-----
      REAL A,B,TAV,OLDVISC,SMOOTH
      INTEGER I,J
#INCLUDE: 'COMMON.FOR'
      IF (IOFLAG.EQ.3) WRITE(*,'(A,4F12.5)') ' VIS,T:',VISO,VIS1,TO,T

      B=ALOG(VISO/VIS1)/(1/TO-1/T1)
      A=VISO*EXP(-B/TO)

      DO 200 J=1,TYPE
      OLDVISC=VISC(2,J)
C      The old value of viscosity is stored; it is used
c      to smooth the viscosity fluctuations during Temp.-visc.
c      distortion iterations.
      DO 100 I=2,M+1
          TAV=(T(I,J)+T(I-1,J))/2
          VISC(I,J)=A*EXP(B/TAV)

100      CONTINUE
          SMOOTH= .6 + .4*OLDVISC/VISC(2,J)
C      The current viscosity will depend approx. 40% on
c      the previous viscosity. This smoothing is required
c      to stabilize the iterations.
      DO 150 I=2,M+1
          VISC(I,J)=VISC(I,J)*SMOOTH

150      CONTINUE

          VISC(1,J)=VISC(2,J)
C      (the vis. of the point just before the pad is assumed
C      to have the same vis. as the next point. This may not
C      be the best assumption, but it is not critical)
200      CONTINUE

      RETURN
      END

```

```
C-----
C      SUBROUTINE GXGZ
C      Aug. 10
C      GX,GZ,CF are found as a functions of film thickness.
C-----

      REAL RE,HAV,QX
      INTEGER I,J

      #INCLUDE: 'COMMON.FOR'

      DO 200 J=1,TYPE
        DO 100 I=2,M+1

          HAV=(H(I,J)+H(I-1,J))/2
          QX=U*HAV/2
          Calc. Reynold's No. RE
          RE=RO*QX/VISC(I,J)
          GX(I,J)=1/(12+.0136*RE**.9)
          GZ(I,J)=1/(12+.0043*RE**.96)
          CF(I,J)=1+.0012*RE**.94
          note.see p.75 of E.R.BOOSER

C      100      CONTINUE
C      The Gx,Gz,Cf values at the pad end are assumed to be
C      the same as for the next interval for convenience.
C
          GX(1,J)=GX(2,J)
          GZ(1,J)=GZ(2,J)
          CF(1,J)=CF(2,J)

C      200      CONTINUE
C      RETURN
C      END
```

C:\msoft1>type distort.for

```

C-----
C      SUBROUTINE DISTORT(J,P)
C              JAN. 16,1985
C-----
C  SUMMARY:  This routine calculates THERMAL and ELASTIC deflections
C            given : a) pad pressures
C                   b) pad temp. distrubution
C                   c) pad thickness, radius of curv., Young's Modula
C                   d) thermal coef. of expansion.
C            The routine is divided into 7 sections:
C                   a) initial non-executable statements
C                   b) calculation of routine constants
C                   c) set up range for DO loops
C                   d) calc. bending moment for grid points to the
C                     left of the pivot.
C                   e) cal. bend. moment for pts. to the right of
C                     pivot
C                   f) working away from pivot, find deflections
C                     (left of pivot)
C                   g) working away from pivot, find deflections
C                     (right of pivot)
C-----
C a)
      REAL SLOPE,CURVE,A,RBAR,RN,EARR,PIVPOS,DTHT
      REAL CS,SN,HCS,HSN, FP
      REAL P
      INTEGER NB,NA
      INTEGER J
      DIMENSION P(20,8), CURVE(20)
      #INCLUDE 'COMMON.FOR'
C b)
      C  A is pad cross section area; RBAR=radius of centroid of A;
      C  RN=radius of neutral axis of the couved beam;EARR is a
      C  convenient grouping of variables; DTHT=angular grid spacing.
      A=BR*THICK
      RBAR=R+THICK/2
      RN=THICK/ALOG((R+THICK)/R)
      EARR=E*A*R*(RBAR-RN)
      DTHT=DX/R
C c)
      C  NB,NA=# of nodes before and after pivot.
      C  The pivot is in general at some point between two nodes.
      NB=1+THTL/DTHT
      NA=M+1-NB
      PIVPOS=(THTL-(NB-1)*DTHT)/DTHT

      CS=COS(DTHT)
      SN=SIN(DTHT)
      HCS=COS(DTHT/2)
      HSN=SIN(DTHT/2)
C d)
      C  Specify bending moment,shear force, tensile force and curvature
      C  at the end of the pad.
      BENDM(1)=0
      SHEAR(1)=0
      TENS(1)=0
      CURVE(1)=0
C  integrate up to pivot:
      DO 100 I=2,NB

```

```

C   Calc. the pressure load FP over a node based on the average
C   pressure knowing the axial pressure profile.
      FP=P(I,J)*NE/(NE+1)*DX*BR

C   Using statics, determine the forces on one grid element:
      TENS(I)=TENS(I-1)*CS+SHEAR(I-1)*SN
C       +FP*HSN

      SHEAR(I)=SHEAR(I-1)*CS-TENS(I-1)*SN
C       + FP*HCS

      BENDM(I)=BENDM(I-1)-SHEAR(I-1)*RN*SN
C       +TENS(I-1)*RN*(1-CS)-FP*RN*HSN

C   The pad curvature is the sum of elastic and thermal bending;
C   the thermal distortion is based on a temperature difference
C   of (pad temperature-oil supply temperature) rather than
C   a temperature difference derived from a heat balance.
C   (ie, using the power loss and pad thermal resistance)
      CURVE(I)=BENDM(I)/EARR-ALF*(T(I,J)-TSUP)/THICK

100   CONTINUE
C e)
C   set end of pad conditions:
      BENDM(M+1)=0
      SHEAR(M+1)=0
      TENS(M+1)=0
      CURVE(M+1)=0
C   integrate up to pivot:
      DO 200 I=M,NB+1,-1

          FP=P(I,J)*NE/(NE+1)*DX*BR

          TENS(I)=TENS(I+1)*CS+SHEAR(I+1)*SN
C           +FP*HSN

          SHEAR(I)=SHEAR(I+1)*CS-TENS(I+1)*SN
C           +FP*HCS

          BENDM(I)=BENDM(I+1)-SHEAR(I+1)*RN*SN
C           +TENS(I+1)*RN*(1-CS)
C           -FP*RN*HSN

          CURVE(I)=BENDM(I)/EARR-ALF*(T(I,J)-TSUP)/THICK

200   CONTINUE

C f)
C   calculate average slope for the first interval away from the
C   pivot:
      AVCURV=(CURVE(NB)+CURVE(NB+1))/2
      SLOPE=AVCURV*PIVPOS*DX/2
      DSTRT(NB,J)=SLOPE*PIVPOS*DX
C   integrate to get deflections for other points:
      DO 300 I=NB-1,1,-1

```

```

        SLOPE=SLOPE+CURVE(I+1)*DX
        DSTRT(I,J)=SLOPE*DX+DSTRT(I+1,J)-1.5*SHEAR(I)*DX/G/A
300    CONTINUE
C g)
C    calculate average slope for the first interval away from the
C    pivot:
        AVCURV=(CURVE(NB)+CURVE(NB+1))/2
        SLOPE=AVCURV*(1-PIVPOS)*DX/2
        DSTRT(NB+1,J)=SLOPE*(1-PIVPOS)*DX
C integrate to get deflections for other points:
        DO 400 I=NB+2,M+1

            SLOPE=SLOPE+CURVE(I-1)*DX
            DSTRT(I,J)=SLOPE*DX+DSTRT(I-1,J)-1.5*SHEAR(I)*DX/G/A
400    CONTINUE

        IF(IOFLAG.NE.3) GOTO 600
C    output results for debugging
        WRITE(*,'(A,6X,A)') ' I',
C'P      TENS      SHEAR      BENDM      CURVE      DIST'
        DO 500 I=1,M+1

            WRITE(*,'(I3,E10.4,5E12.5)') I,P(I,J),TENS(I),SHEAR(I),BENDM(I
C      ,CURVE(I),DSTRT(I,J)
500    CONTINUE
600    CONTINUE
        RETURN
        END

```

```
C-----  
C          SUBROUTINE PRELOAD(PRLD)  
C          Aug. 10  
C This routine calculates the SHAPE of a prloaded pad relative  
C to a fitted pad.  
C          PRLD - PRELOAD=(C-CL)/C    (the pad is machined to radius  
C                                     R+C, CL is clearance at pivot)  
C          SHAPE - always less than 0 for a preloaded pad.  
C-----
```

```
          REAL PRLD,DTHT,THT,DC  
          INTEGER I  
$INCLUDE : 'COMMON.FOR'  
  
          DTHT=(THTL+THTT)/M  
          DC=PRLD/(1-PRLD) * CL  
  
          DO 100 I=1,M+1  
             THT=DTHT*(I-1)-THTL  
             SHAPE(I)=-DC*(1-COS(THT))  
100      CONTINUE  
  
          RETURN  
          END
```

```

C-----
C      SUBROUTINE GEOM(J,PHI,VPHI)
C      January 22, 1985
C      Film thickness (H) and rate of change of film thickness (VH) is
C      calculated for all grid points of the specified pad. Independent
C      variables are: ECC,VECC,PSI,VPSI, PHI. Also,bearing size is an input
C      SHAPE: Loss of film thickness due to preload
C      DSTRT: " " " " " thermal , elastic distortions
C-----
C      REAL PHI,VPHI
C      INTEGER J
C      REAL THT,DTH
C      $INCLUDE: 'COMMON.FOR'

C      Scrape is a flag to indicate (if scrape>0) that the pad tilt
C      given is physically impossible.
C      SCRAPE=0

C      The angular coordinate THT is referenced to the leading
C      edge of the pad pivot rather than the pivot.
C      THTI=THTO(J)-THTL
C      DTH=DX/R

C      DO 100 I=1,M+1
C      THT=THTI+DTH*(I-1)
C      H(I,J)=CL*(1-ECC*COS(THT-PSI))-PHI*(R+BP)*SIN(THT-THTO(J))
C      -SHAPE(I) -DSTRT(I,J)
C      VH(I,J)=VPSI*ECC*CL*SIN(THT-PSI)-VPHI*(R+BP)*SIN(THT-THTO(J))
C      -VECC*CL*COS(THT-PSI)

C      IF ( H(I,J).LT.0 ) SCRAPE=1
C      A negative film thickness is impossible.

100  CONTINUE
      RETURN
      END

```

```

C-----
C      SUBROUTINE FILM(J,P)
C      MARCH 14, 1985
C      Film pressures are found for points between those points at which
C      VISC,GX,GZ,CF are defined. Independent variables are: visc,Gx,Gz
C      H,dH/dt. NE is the "Schelly Exponent ",depending on pad shape
C      ,chosen so that the approximate method of solution used is accurate
C-----
      REAL P
      INTEGER J
      REAL A,B,C,D, AM,BM,CM,DM,EM, GM
      INTEGER I
      DIMENSION AM( 20),BM( 20),CM( 20),DM( 20),EM(20),GM( 20)
      DIMENSION P(20,8)
      #INCLUDE: 'COMMON.FOR'

C      First, the finite difference matrix is calculated...
      DO 100 I=2,M

          A=(GX(I,J)+GX(I+1,J))/(VISC(I,J)+VISC(I+1,J))*
            H(I,J)**3*NE/(NE+1)
          B=(GX(I+1,J)/VISC(I+1,J)*(H(I+1,J)+H(I,J))**3/8-
            GX(I,J)/VISC(I,J)*(H(I,J)+H(I-1,J))**3/8) / DX
            *NE/(NE+1)
          C=-(GZ(I,J)+GZ(I+1,J))/(VISC(I,J)+VISC(I+1,J))*H(I,J)*
            *(2/BR)**2 * NE
          D=U/2*(H(I+1,J)-H(I-1,J))/2/DX + VH(I,J)

          AM(I)=A/DX**2-B/(2*DX)
          BM(I)=C-2*A/DX**2
          CM(I)=A/DX**2+B/(2*DX)
          DM(I)=D

100      CONTINUE

C      Next, the matrix is reduced to a two band matrix.
      GM(2)=BM(2)
      EM(2)=DM(2)
      DO 200 I=3,M

          GM(I)=BM(I)-AM(I)*CM(I-1)/GM(I-1)
          EM(I)=DM(I)-AM(I)*EM(I-1)/GM(I-1)

200      CONTINUE

C      Finally, the pressures are found by back substitution.
C      All negative pressures are set to 0 AFTER they are used to
C      calculate the next pressure.
      DO 300 I=M,2,-1

          P(I,J)=(EM(I)-CM(I)*P(I+1,J))/GM(I)
          IF(P(I+1,J).LT.0) P(I+1,J)=0.0

300      CONTINUE
      IF(P(2,J).LT.0) P(2,J)=0.0
      RETURN
      END

```

C:\msoft1>type heat.for

```

C-----**
C      SUBROUTINE HEAT(P)
C                                     MARCH 14, 1985
C The pad temperature distrubution is calculated for the whole bearing
C given the pressures, film thicknesses and oil properties. Note that
C oil pressure is dependent on viscosity, which is dependent on T.
C-----

      REAL P
      REAL DTDX,DPDX,PDPDX,PDPDZ, SH,AVSH,QX,QZ, YH
      REAL CX,CZ,CSH ,CPOW,NPOW,NU,KR
      REAL QR, TIN , HAV
      INTEGER ACROSS
      DIMENSION P(20,8),QSIDE(8)
#INCLUDE: 'COMMON.FOR'

C      FIND TEMP.DIFFERENCES ALONG PADS, FLOWS, POWER LOSSES

C For an estimate of the power loss, curve fitting has been used.
C NU,CPOW,NPOW are parameters in the empirical equation used.
C Jakobsson,B. and Floberg,L."The Rectangular Plane Bearing",
C Transactions of the Chalmers University of Tech., Gothenberg,
C Sweden, 1958, pp.29-31

      NU=BR/(THTT+THTL)/R
      CPOW=EXP(-1.5*TANH(.363*NU+.877))
      NPOW=.4146
C These parameters are used only in the "empirical" section of HEAT.

c Start the calculation of temperatures using the marching
c procedure described by Ettles.(Ettles,C.M., " The Analysis
c and Performance of Pivoted Pad Journal Bearings Considering
c Thermal and Elastic Effects", Transactions of the ASME
c 79-Lub-31 pp 1-10

      DO 500 J=1,TYPE
      POWER(J)=0.0

C      FOR EACH GRID INTERVAL...
      DO 400 I=2,M+1
      DTDX=0
      AVSH=0
C The temp. gradient DTDX and the shaft shear stress AVSH
c are accumulated across the pad for averaging. Therefore,
c they are initialized to 0.
      HAV=(H(I,J)+H(I-1,J))/2
      DPDX=(P(I,J)+P(I-1,J))/DX
      CPZ=-NE/BR*(P(I,J)+P(I-1,J))
      CX=GX(I,J)*HAV**3/VISC(I,J)
      CZ=GZ(I,J)*HAV**3/VISC(I,J)
      CSH=CF(I,J)*VISC(I,J)*U/HA

```

```

C      AVERAGING VALUES ACROSS PAD...
      DO 300 ACRSS=0,4
        YH=ACRSS/4.0
        PDPDX=DPDX*(1-YH**NE)
        PDPDZ=CPZ*YH**(NE-1)
        QX=-CX*PDPDX+U*HAV/2
        QZ=-CZ*PDPDZ
        SH=CSH+HAV/2*PDPDX
        AVSH=AVSH+SH/5
        DTDX=DTDX+(SH*U-QX*PDPDX-QZ*PDPDZ)/QX/5
300      CONTINUE

      T(I,J)=T(I-1,J)+DTDX/(RO*CP) *DX*ABSRB
      POWER(J)=POWER(J)+U*BR*DX*AVSH
400      CONTINUE

      QLAST(J)=(-DPDX*(NE/(NE+1))*CX + U*HAV/2 ) * BR
      HAV=(H(2,J)+H(1,J))/2
      DFDX=(P(2,J)-P(1,J))/DX* NE/(NE+1)
      CX=GX(2,J)*HAV**3 /VISC(2,J)
      QIN(J)=(-DFDX*(NE/(NE+1))*CX +U*HAV/2 ) * BR

c Calculation of power loss by the empirical curve fit:
      IF (HFLAG.GE.3) THEN
        KR=((H(1,J)/H(20,J)-1.0)/2+ABS(H(1,J)/H(20,J)-1.0)/2+.01)**NFC
        POWER(J)=VISC(14,J)*U*U*BR*R*(THTT+THTL)/H(20,J) *(1-CPOW*KR)
      C  *CF(14,J)
      ELSE
        CONTINUE
      END IF

C If desired, it is possible to calculate the temperatures according
c to the Jones and Martin method. The idea is to calculate an
c effective temperature rise DTEFF. This method will be used if HFLAG
c is GE 2. (G.J. Jones and F.A. Martin, "Geometry Effects", ASLE
c Trans. Vol. 22.3,227-224.)
      IF (HFLAG.GE.2) THEN
        TEFF(J)=T(1,J)+2*ABSRB*POWER(J)/(QLAST(J)+QIN(J))/RO/CP
        T(20,J)=TEFF(J)+2/3*(TEFF(J)-T(1,J))
        DO 520 I=2,M
          T(I,J)=(T(20,J)-T(1,J))*I/19 + T(1,J)
520      CONTINUE

        ELSE
          CONTINUE
        END IF

500      CONTINUE

```

```
C          NOW USE GROOVE MIXING THEORY TO RELATE THE PAD T's
C (Ettles,p.4)
C          TIN=T(1,1)
C          {the first iteration arbitrarily assumes T(1,1) is correct}

600          CONTINUE
C          {all iterations after the first start here}

          DO 800 J=1,TYPE
            DO 700 I=2,M+1
              T(I,J)=T(I,J)+TIN-T(1,J)
700          CONTINUE
            T(1,J)=TIN
C          QR is an indication of the amount of hot oil carry-over.
C          As QR rises, so does the overall bearing temperature.
C          It is possible that the hot side oil leakage will be carried
C          over (in addition to the end leakage). If this is to be taken into
C          account, QR should be increased by some factor between 1 and 2
            IF (J.EQ.TYPE) THEN
              QR=QLAST(TYPE)/QIN(1)
            ELSE
              QR=QLAST(J)/QIN(J+1)
            END IF
            IF (QR.LT.0.1) QR=.1
            IF (QR.GT.0.9) QR=.9
            TEFF(J)=3/5*(T(20,J)+2/3*T(1,J))
C          {Teff has been recalculated because groove mixing calc's
C          have changed all of the temperatures}
            TIN=T(M+1,J)*QR+ TSUP*(1-QR)
800          CONTINUE

          IF (ABS(TIN-T(1,1)).GT.TTOL) GO TO 600
C          {continue iterations}

          RETURN
          END
```

```

C-----
C      SUBROUTINE INTGL(J,P,DTHT)
C      MARCH 14, 1985
C      The P distrubution for pad J is integrated to give x,y components
C      . Also, the line of action of the pad's load is compared to the
C      loaction of the pivot. The differnce in angle is DTHT.
C-----
      REAL P,PAV
      REAL DTHT
      REAL THTF,DA,THTI, DTH
      INTEGER J
      DIMENSION P(20,8)
*INCLUDE: 'COMMON.FOR'

      FX(J)=0
      FY(J)=0
      DA=DX*BR
C      DA is the area element of integration.
      THTI=THTO(J)-THTL
      DTH=(THTT+THTL)/M

      DO 100 I=2,M+1
        PAV=(P(I,J)+P(I-1,J))/2 * NE/(NE+1)
        SH=CF(I,J)*VISC(I,J)*U*2/(H(I,J)+H(I-1,J)) +
C      (H(I,J)+H(I-1,J))*(P(I,J)-P(I-1,J))/4/DX * NE/(NE+1)
        THT=THTI+DTH*(I-1.5)
        FX(J)=FX(J)+ (PAV*COS(THT)-SH*SIN(THT)) * DA
        FY(J)=FY(J)+ (PAV*SIN(THT)+SH*COS(THT)) * DA
100    CONTINUE

C      NOW FIND THE LINE OF ACTION OF FX(J),FY(J) AN COMPARE WITH THTO(J)
      IF(FY(J).GT.0) THEN
C      {the force ON THE PAD is acting at an angle on [0,pi]
        IF(FX(J).EQ.0.0) THEN
          THTF=PI/2.0
        ELSE
          IF(FX(J).GT.0) THEN
            THTF=ATAN(FY(J)/FX(J))
          ELSE
            THTF=PI+ATAN(FY(J)/FX(J))
          END IF
        END IF
      ELSE
C      {the force is acting at an angle on [pi,2pi] }
        IF(FX(J).EQ.0.0) THEN
          THTF=3*PI/2
        ELSE
          IF(FX(J).GT.0) THEN
            THTF=2*PI+ATAN(FY(J)/FX(J))
          ELSE
            THTF=PI + ATAN(FY(J)/FX(J))
          END IF
        END IF
      END IF
      DTHT=THTF-THTO(J)
      IF(DTHT.GT.PI) DTHT=DTHT-2*PI
C      {if DTHT>pi, the force is behind the pivot by an angle
C      DTHT-2pi.

      RETURN
      END

```

```
C-----  
C      SUBROUTINE SUMFORCE  
C  
C      MARCH 7, 1985  
C  
C This routine adds up the forces on each pad. The pad forces  
c are stored in the variables FX(J), FY(J). Both variables are in  
c the COMMON statement.  
C-----  
C      INTEGER J  
C      $INCLUDE: 'COMMON.FOR'  
C  
C      TOTX=0.0  
C      TOTY=0.0  
C  
C      DO 10 J=1,TYPE  
C          TOTX=TOTX+ FX(J)  
C          TOTY=TOTY + FY(J)  
10  CONTINUE  
C  
C      TOTAL=SQRT(TOTX**2 +TOTY**2)  
C  
C      RETURN  
C      END
```

```

C-----
C      SUBROUTINE WHOLE(P,PRLD)
C      APRIL 11,1985
C-----

C      This routine finds the steady-state pad positions and loads
C      for a bearing with given eccentricity, speed,dimmmensions.

      REAL AXX,AXY,AYX,AYY,XSTEP,YSTEP
      REAL BXX,BXY,BYX,BYY,VXSTEP,VYSTEP
      REAL P,DTHT,PRLD
      INTEGER J
      DIMENSION P(20,8)
$INCLUDE: 'COMMON.FOR'
C Output bearing description.
      WRITE(4, '(A,I3)') ' NO. OF PADS :',TYPE
      WRITE(4, '(A,2F12.3)') ' LEADING, TRAILING EXTENT:',THTL,THTT
      WRITE(4, '(A)') ' Pad Positions from x axis in radians,ccw'
      WRITE(4, '(8F9.3)') (THT0(J),J=1,8)

      WRITE(4, '(7X,A,13X,A,13X,A,13X,A,10X,A)') ' R','BR','CL','BP',
C 'PRELOAD'
      WRITE(4, '(F12.8,3F15.8,F15.8)') R,BR,CL,BP,PRLD

      WRITE(4, '(3X,A,7X,A,7X,A,7X,A,12X,A,8X,A,8X,A)') 'VISO',
C 'TO','VIS1','T1','RO','CP','TSUP'
      WRITE(4, '(4F10.5,3F11.4)') VISO,TO,VIS1,T1,RO,CP,TSUP

      WRITE(4, '(7X,A,13X,A,12X,A,11X,A,12X,A)') 'W','ECC','VECC',
C 'PSI','VPSI'
      WRITE(4, '(F10.3,4F15.8)') W,ECC,VECC,PSI,VPSI

      WRITE(4, '(3X,A,6X,A,8X,A,10X,A,8X,A)') 'GRID SIZE',
C 'TOLTLT','TTOL','NE','ABSRB'
      WRITE(4, '(I8,4X,4F13.7)') M,TOLTLT,TTOL,NE,ABSRB

      WRITE(4, '(A)') '
      WRITE(4, '(A,F8.2)') ' ELASTIC MODULAS (GPa) =',E/10000000000.
      WRITE(4, '(A,F8.2)') ' SHEAR MODULAS (GPa) =',G/10000000000.
      WRITE(4, '(A,F8.3)') ' STRAIN/DEG. C (*E5) =',ALF*100000.
      IF(HFLAG.EQ.1) WRITE(4, '(A)') ' ETTLES HEAT BAL.'
      IF(HFLAG.EQ.2) WRITE(4, '(A)') ' SH. STRSS POW.;MARTIN BAL.
      IF(HFLAG.EQ.3) WRITE(4, '(A)') ' EMP'CL POW.; MARTIN BAL.
      WRITE(4, '(A,I3)') ' # OF ITERATIONS=',ITTRT

      CALL PRELOAD(P,PRLD)
      DO 30 NITT=1,ITTRT

```

```

      CALL VISFLD
      DO 20,J=1,TYPE
        CALL BALANCE(J,P)
        CALL DISTORT(J,P)
20      CONTINUE
      CALL GXGZ
      CALL HEAT(P)
      CALL SUMFORCE

30      CONTINUE

      CALL OUTPUT(P)
      CALL STIFF(AXX,AXY,AYX,AYY,XSTEP,YSTEP)
      WRITE(4, '(A)')
C      '      AXX      AXY      AYX      AYY(non-dim. by CL/TOTAL)
      WRITE(4, '(4F10.6)') AXX,AXY,AYX,AYY
      CALL DAMP(BXX,BXY,BYX,BYY,VXSTEP,VYSTEP)
      WRITE(4, '(A)')
C      '      BXX      BXY      BYX      BYY non-dim. by CL/TOTAL*W
      WRITE(4, '(4F10.6)') BXX,BXY,BYX,BYY

      WRITE(4, '(A)') ' '
      CALL LTSDAT(P,PRLD,AXX,AXY,AYX,AYY,BXX,BXY,BYX,BYY)

      RETURN
      END
```

```

C-----
C      SUBROUTINE OUTPUT(P)
C      APRIL 11, 1985
C-----
C This routine outputs the bearing performance; it does not echoe
C input conditions.

      INTEGER I,J
      REAL P,XL,HMM,DMM

      DIMENSION P(20,8)
      #INCLUDE: 'COMMON.FOR'

      SUMP=0.0
      DO 3000 J=1,TYPE

        SUMP=SUMP+POWER(J)
        WRITE(4, '( /A,I3) ' ) ' PAD #',J
        RESLT=SQRT(FX(J)**2+FY(J)**2)
        WRITE(4, '(A) ' )

C' POWER (W)   LOAD (N) Qin-Qlast ml/s   Hin/Hout   Tin   Tout
C Visc @piv'
        WRITE(4, '(2F10.0,F12.6,F12.3,2F9.1,F10.5) ' ) POWER(J),RESLT,
C 1000000*(QIN(J)-QLAST(J)),H(1,J)/H(20,J),T(1,J),T(20,J),
C VISC(10,J)

        IF (IOFLAG.EQ.1) GOTO 3000
        WRITE(4, '(A,A) ' ) ' X/L h(mm) visc(Pa-s)   P(Pa) ',
C ' --> distort(mm)   Gx   Gz   Cf   T'
        K=9
        IF (IOFLAG.EQ.3) K=2

        DO 2000 I=1,19,K

          XL=(I-1)/19.0
          HMM=H(I,J)*1000.
          DMM=DSTRT(I,J)*1000.
          WRITE(4, '(F4.2,F7.4,F8.5,F12.0,F10.4,5X,3F8.5,F6.1) ' )
C XL,HMM,VISC(I,J),P(I,J),DMM,GX(I,J),GZ(I,J),CF(I,J),T(I,J)
2000    CONTINUE

3000    CONTINUE
        WRITE(4, '( /) ' )
        WRITE(4, '( /A) ' ) ' Bearing totals:'
        WRITE(4, '(A,F12.2) ' ) ' LOAD (kN)=',TOTAL/1000.
        WRITE(4, '(A,F6.1) ' ) ' Load angle(deg.)=',ATAN(TOTY/TOTX)*57.3
        WRITE(4, '(A,F12.1) ' ) ' POWER(W)=', SUMP

C The Sommerfeld No. is calculated with an average viscosity.
c Turbulence is ignored.
        VISSUM=0
        DO 5000 J=1,TYPE
          VISSUM=VISSUM+VISC(10,J)
5000    CONTINUE
        VISAV=VISSUM/TYPE
        SOMMER=(R/CL)**2*VISAV*(W/2/PI)/TOTAL*2*R*BR
        WRITE(4, '(A,F12.6) ' ) ' Sommerfeld # =',SOMMER
        RETURN
      END

```

SUBROUTINE STORAGE

c this routine allows bearing description data (ie,size) to be
c stored or recalled from user specified files.

C MARCH 14,1985

INTEGER J
CHARACTER*64 FNAME
\$INCLUDE: 'COMMON.FOR'

WRITE(*,'(A)\') ' Do you want to store or recall data? 1=store
READ(*,'(I2)\') II
WRITE(*,'(A)\') ' FILENAME ?'
READ(*,'(A)\') FNAME
IF (II.EQ.1) THEN

CCCCCCC STORE DEFAULT BEARING CCCCCC

OPEN(3,FILE=FNAME,STATUS='NEW')

WRITE(3,'(I16)\') TYPE

DO 10 J=1,8

10 WRITE(3,'(E16.4)\') THTO(J)

CONTINUE

WRITE(3,'(E16.4)\') THTT

WRITE(3,'(E16.4)\') THTL

WRITE(3,'(E16.4)\') R

WRITE(3,'(E16.4)\') BR

WRITE(3,'(E16.4)\') CL

WRITE(3,'(E16.4)\') BP

WRITE(3,'(E16.4)\') PRLD

WRITE(3,'(E16.4)\') VISO

WRITE(3,'(E16.4)\') TO

WRITE(3,'(E16.4)\') VISI

WRITE(3,'(E16.4)\') T1

WRITE(3,'(E16.4)\') RO

WRITE(3,'(E16.4)\') CP

WRITE(3,'(E16.4)\') TSUP

WRITE(3,'(E16.4)\') W

WRITE(3,'(E16.4)\') ECC

WRITE(3,'(E16.4)\') VECC

WRITE(3,'(E16.4)\') PSI

WRITE(3,'(E16.4)\') VPSI

DO 15 J=1,8.

15 WRITE(3,'(E16.4)\') PHIO(J)

CONTINUE

WRITE(3,'(E16.4)\') TEMPO

WRITE(3,'(I16)\') M

WRITE(3,'(E16.4)\') TOLTLT

WRITE(3,'(E16.4)\') TTOL

WRITE(3,'(E16.4)\') NE

WRITE(3,'(E16.4)\') ABSRB

WRITE(3,'(E16.4)\') Y

WRITE(3,'(E16.4)\') E

WRITE(3,'(E16.4)\') G

WRITE(3,'(E16.4)\') ALF

WRITE(3,'(E16.4)\') SHFACT

WRITE(*,'(A,A)') ' DATA STORED IN ',FNAME

CCCCCC READ IN DEFAULT BEARING DESCRIPTION
ELSE

OPEN(3,FILE=FNAME,STATUS='OLD')

READ(3,'(I16)') TYPE

DO 20 J=1,8

20 READ(3,'(E16.4)') THTO(J)
CONTINUE

READ(3,'(E16.4)') THTT

READ(3,'(E16.4)') THTL

READ(3,'(E16.4)') R

READ(3,'(E16.4)') BR

READ(3,'(E16.4)') CL

READ(3,'(E16.4)') BP

READ(3,'(E16.4)') PRLD

READ(3,'(E16.4)') VISO

READ(3,'(E16.4)') TO

READ(3,'(E16.4)') VIS1

READ(3,'(E16.4)') T1

READ(3,'(E16.4)') RO

READ(3,'(E16.4)') CP

READ(3,'(E16.4)') TSUP

READ(3,'(E16.4)') W

READ(3,'(E16.4)') ECC

READ(3,'(E16.4)') VECC

READ(3,'(E16.4)') PSI

READ(3,'(E16.4)') VPSI

DO 25 J=1,8

25 READ(3,'(E16.4)') PHIO(J)
CONTINUE

READ(3,'(E16.4)') TEMPO

READ(3,'(I16)') M

READ(3,'(E16.4)') TOLTLT

READ(3,'(E16.4)') TTOL

READ(3,'(E16.4)') NE

READ(3,'(E16.4)') ABSRB

READ(3,'(E16.4)') Y

READ(3,'(E16.4)') E

READ(3,'(E16.4)') G

READ(3,'(E16.4)') ALF

READ(3,'(E16.4)') SHFACT

WRITE(*,'(A,A)') ' DATA READ IN FROM ',FNAME

CCCCCC FINISHED
END IF
RETURN
END

```
C-----
C  SUBROUTINE LTSDAT(P,PRLD,AXX,AXY,AYX,AYY,BXX,BXY,BYX,BYY)
C  APRIL 28,1986
C-----

REAL P,TPOW,PRLD,AXX,AXY,AYX,AYY,BXX,BXY,BYX,BYY
INTEGER I,J,K
DIMENSION P(20,8)

$INCLUDE: 'COMMON.FOR'
      TPOW=POWER(1)+POWER(2)+POWER(3)+POWER(4)+POWER(5)+POWER(6)
C    +POWER(7)+POWER(8)
      VISSUM=0
      DO 50 J=1,TYPE
        VISSUM=VISSUM+VISC(10,J)
50    CONTINUE
      VISAV=VISSUM/TYPE
      SOMMER=(R/CL)**2*VISAV*W*R*BR/TOTAL/PI
      WRITE(7,'(2X)')
      WRITE(7,'(2X)')
      WRITE(7,'(6F15.6)') W,ECC,PSI,TOTAL,TPOW,SOMMER
      WRITE(7,'(2X)')
      WRITE(7,'(6F15.6)') ABSRB,E/10**9,ALPHA,PRLD,THTL,THTT
      WRITE(7,'(2X)')

      DO 100 J=1,8
        WRITE(7,'(I2,14F15.6)') J,PHIO(J),FX(J),FY(J),POWER(J),QIN(J)
C      QLAST(J),T(1,J),T(20,J),H(1,J),H(20,J),VISC(10,J),GX(10,J)
C,DSTRT(1,J)/CL,DSTRT(20,J)/CL
100    CONTINUE
      WRITE(7,'(2X)')
      WRITE(7,'(2X,8F15.3)') AXX,AXY,AYX,AYY,BXX,BXY,BYX,BYY
      WRITE(7,'(2X)')

      RETURN

      END
```

CCC

common.for
APRIL 29, 1986

```
REAL H,VH,ECC,VECC,PSI,VPSI,SHAPE , THTO,THTL,THTT
REAL R,BR,CL,BP ,DX, VISC,VISO,VISI,TO,TI
REAL T,TSUP,TEFF,CP,POWER,QLAST,QIN,TTOL,TOLTLT,ABSRB
REAL CF,GX,GZ,U,W,RO
REAL NE,PI,Y,PHIO,VPHIO
REAL BENDM,SHEAR,TENS, E,G, DSTRT, THICK,ALF
INTEGER M,TYPE,SCRAPE,ITTRT,HFLAG,IOFLAG
REAL FX,FY,TOTX,TOTY,TOTAL
CHARACTER DATE*70
```

```
COMMON/B1/ H,VH,ECC,VECC,PSI,VPSI,SHAPE , THTO,THTL,THTT
COMMON/B2/ R,BR,CL,BP ,DX, VISC,VISO,VISI,TO,TI
COMMON/B3/ T,TSUP,TEFF,CP,POWER,QLAST,QIN,TTOL,TOLTLT,ABSRB
COMMON/B4/ CF,GX,GZ,U,W,RO
COMMON/B6/M,TYPE,SCRAPE,ITTRT,HFLAG,IOFLAG
COMMON/B5/ NE,PI,Y,PHIO,VPHIO
COMMON/B6/ BENDM,SHEAR,TENS,E,G,DSTRT,THICK,ALF
COMMON/B7/ FX,FY,TOTX,TOTY,TOTAL
COMMON/B8/ DATE
```

```
DIMENSION H(20,8),VH(20,8), THTO(8), VISC(20,8)
DIMENSION T(20,8), CF(20,8),GX(20,8),GZ(20,8),SHAPE(20)
DIMENSION POWER(8),TEFF(8),QLAST(8),QIN(8)
DIMENSION DSTRT(20,8), PHIO(8),VPHIO(8)
DIMENSION BENDM(20),SHEAR(20),TENS(20)
DIMENSION FX(8),FY(8)
```

```
OPEN(4,FILE='LPT1')
```

C Data can be sent to the printer directly using unit # 4.

CCC
CCC

```

C*****
SUBROUTINE STIFF(AXX,AXY,AYX,AYY,XSTEP,YSTEP)
C      march 13, 1986
C*****
      REAL AXX,AXY,AYX,AYY,XSTEP,YSTEP,TOTXF,TOTXB,TOTYF,TOTYB
      REAL AO,ECCSTEP,PSISTEP, P
      DIMENSION P(20,8)
$INCLUDE:'COMMON.FOR'
C The step size is set arbitrarily to a reasonable value.
      XSTEP=CL/100
      YSTEP=XSTEP
      WRITE(*,'(A)') ' CALCULATING STIFFNESS'

C Convert from polar to rectangular coordinates
      X=ECC*CL*COS(PSI)
      Y=ECC*CL*SIN(PSI)
      WRITE(*,'(A,F12.6,A,F12.6)') ' X=',X,' Y=',Y

C Calculate the constant for non-dimensionalizing results
      DO 5 J=1,TYPE
C If the pad is unloaded, it is skipped
      IF((FX(J).EQ.0).AND.(FY(J).EQ.0)) GOTO 5
      CALL BALANCE(J,P)
5      CONTINUE
      CALL SUMFORCE
      AO=TOTAL/CL
      WRITE(*,'(A,E15.5)') ' AO=LOAD/CL=',AO

C First, hold y constant
      PSISTEP=Y*XSTEP/(X**2+Y**2)
      ECCSTEP=X*XSTEP/(CL**2 *ECC)

C Calculate forces in position x-xstep
      ECC=ECC-ECCSTEP
      PSI=PSI-PSISTEP

      DO 10 J=1,TYPE
      IF((FX(J).EQ.0).AND.(FY(J).EQ.0)) GOTO 10
      CALL BALANCE(J,P)
10     CONTINUE
      CALL SUMFORCE
      TOTXB=TOTX
      TOTYB=TOTY

C Calculate forces in x+xstep position
      ECC=ECC+2*ECCSTEP
      PSI=PSI+2*PSISTEP

      DO 20 J=1,TYPE
      IF((FX(J).EQ.0).AND.(FY(J).EQ.0)) GOTO 20
      CALL BALANCE(J,P)
20     CONTINUE
      CALL SUMFORCE
      TOTXF=TOTX
      TOTYF=TOTY

      AXX=(TOTXF-TOTXB)/(2*XSTEP*AO)
      AXY=(TOTYF-TOTYB)/(2*XSTEP*AO)

```

```
C      Set ECC,PSI back to the original values.
      ECC=ECC-ECCSTEP
      PSI=PSI-PSISTEP
      WRITE(*,'(A,E12.5,A,E12.5)') ' AXI=',AXI,' AYI=',AYI

C Now hold x constant.

      PSISTEP=-X*YSTEP/(X**2+Y**2)
      ECCSTEP=Y*YSTEP/(CL**2 *ECC)

C      Calculate forces in position y-ystep
      ECC=ECC-ECCSTEP
      PSI=PSI-PSISTEP

      DO 30 J=1,TYPE
        IF((FX(J).EQ.0).AND.(FY(J).EQ.0)) GOTO 30
        CALL BALANCE(J,P)
30     CONTINUE
      WRITE(*,'(A)') ' BALANCED'
      CALL SUMFORCE
      TOTXB=TOTX
      TOTYB=TOTY

C      Calculate forces in y+ystep position
      ECC=ECC+2*ECCSTEP
      PSI=PSI+2*PSISTEP

      DO 40 J=1,TYPE
        IF((FX(J).EQ.0).AND.(FY(J).EQ.0)) GOTO 40
        CALL BALANCE(J,P)
40     CONTINUE
      CALL SUMFORCE
      TOTXF=TOTX
      TOTYF=TOTY

      AXI=(TOTXF-TOTXB)/(2*YSTEP*AO)
      AYI=(TOTYF-TOTYB)/(2*YSTEP*AO)

C      Set ECC,PSI back to the original values.
      ECC=ECC-ECCSTEP
      PSI=PSI-PSISTEP
      WRITE(*,'(A,E15.5,A,E15.5)') ' AXI=',AXI,' AYI=',AYI

      RETURN
      END
```

```

C*****
C      SUBROUTINE DAMP(BXX,BXY,BYX,BYY,VXSTEP,YSTEP)
C      MARCH 25, 1986
C*****
      REAL BXX,BXY,BYX,BYY,VXSTEP,VYSTEP,TOTXF,TOTXB,TOTYF,TOTYB
      REAL B0,VECCSTEP,VPSISTEP,P
      DIMENSION P(20,8)
$INCLUDE: 'COMMON.FOR'
C The velocity increment is an arbitrary fraction of CL*W
      VXSTEP=CL/1000*W
      VYSTEP=VXSTEP
      WRITE(*,'(A)') ' CALCULATING DAMPING'
C Convert from polar to rectangular coordinates

      X=ECC*CL*COS(PSI)
      Y=ECC*CL*SIN(PSI)
      WRITE(*,'(A,F12.6,A,F12.6)') ' X=',X,' Y=',Y

C Calculate the constant for non-dimensionalizing results
      DO 5 J=1,TYPE
C      If the pad is unloaded, it is skipped.
          IF((FX(J).EQ.0).AND.(FY(J).EQ.0)) GOTO 5
          CALL BALANCE(J,P)
      5      CONTINUE
          CALL SUMFORCE
          B0=TOTAL/CL/W
          WRITE(*,'(A,E15.5)') ' B0=LOAD/CL=',B0

C First, hold vy=0

      VPSISTEP=Y*VXSTEP/(X**2+Y**2)
      VECCSTEP=X*VXSTEP/(CL**2 *ECC)

C      Calculate forces in position x=-xstep
      VECC=-VECCSTEP
      VPSI=-VPSISTEP

      DO 10 J=1,TYPE
          IF((FX(J).EQ.0).AND.(FY(J).EQ.0)) GOTO 10
          CALL BALANCE(J,P)
      10      CONTINUE
          WRITE(*,'(A)') ' FINISHED BALANCING PADS'
          CALL SUMFORCE
          TOTXB=TOTX
          TOTYB=TOTY

C      Calculate forces with +vx
      VECC=2*VECCSTEP
      VPSI=2*VPSISTEP

```

```

DO 20 J=1,TYPE
  IF((FX(J).EQ.0).AND.(FY(J).EQ.0)) GOTO 20
  CALL BALANCE(J,P)
20 CONTINUE
  WRITE(*, '(A)') ' BALANCED'
  CALL SUMFORCE
  TOTXF=TOTX
  TOTYF=TOTY

  BXX=(TOTXF-TOTXB)/(2*VXSTEP*B0)
  BYX=(TOTYF-TOTYB)/(2*VXSTEP*B0)

C   Reset vecc, vpsi
  VECC=0
  VPSI=0
  WRITE(*, '(A,E12.5,A,E12.5)') ' BXX=',BXX,' BYX=',BYX

C Now hold x constant.

  VPSISTEP=-X*VYSTEP/(X**2+Y**2)
  VECCSTEP=Y*VYSTEP/(CL**2 *ECC)

C   Calculate forces with -vy
  VECC=-VECCSTEP
  VPSI=-VPSISTEP

DO 30 J=1,TYPE
  IF((FX(J).EQ.0).AND.(FY(J).EQ.0)) GOTO 30
  CALL BALANCE(J,P)
30 CONTINUE
  WRITE(*, '(A)') ' BALANCED'
  CALL SUMFORCE
  TOTXB=TOTX
  TOTYB=TOTY

C   Calculate forces with +vy
  VECC=2*VECCSTEP
  VPSI=2*VPSISTEP

DO 40 J=1,TYPE
  IF((FX(J).EQ.0).AND.(FY(J).EQ.0)) GOTO 40
  CALL BALANCE(J,P)
40 CONTINUE
  WRITE(*, '(A)') ' BALANCED'
  CALL SUMFORCE
  TOTXF=TOTX
  TOTYF=TOTY

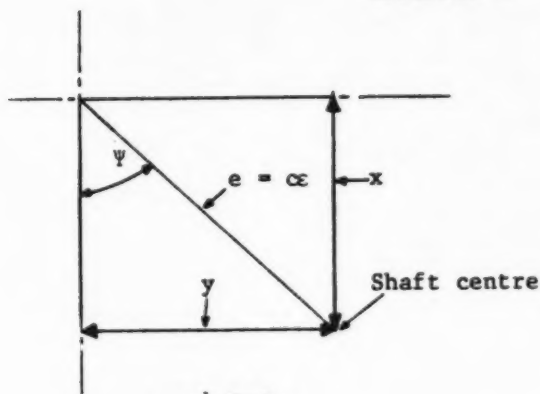
  BXY=(TOTXF-TOTXB)/(2*VYSTEP*B0)
  BYY=(TOTYF-TOTYB)/(2*VYSTEP*B0)

C   Reset VECC,VPSI
  VECC=0
  VPSI=0
  WRITE(*, '(A,E15.5,A,E15.5)') ' BXY=',BXY,' BYY=',BYY

  RETURN
  END

```

- R1 -
APPENDIX B



$$\psi = \tan^{-1} \left[\frac{y}{x} \right]$$

$$d\psi = \frac{d \left[\frac{y}{x} \right]}{1 + \left[\frac{y}{x} \right]^2}$$

$$d\psi = \frac{xdy - ydx}{x^2 + y^2}$$

For small increments of x and y

$$\Delta\psi = \frac{x\Delta y - y\Delta x}{x^2 + y^2} \quad (B1)$$

$$\text{Also, } x = c\epsilon \cos \psi$$

$$y = c\epsilon \sin \psi$$

$$\text{Hence } c^2\epsilon^2 = x^2 + y^2$$

$$d\epsilon = \frac{xdx + ydy}{c^2\epsilon}$$

For small increments of x and y

$$\Delta\epsilon = \frac{x\Delta x + y\Delta y}{c^2\epsilon} \quad (B2)$$

Similarly,

$$\frac{d(\psi)}{dt} = \tan^{-1} \frac{\frac{d(y)}{dt}}{\frac{d(x)}{dt}}$$

For small increments of x and y

$$\Delta\dot{\psi} = \frac{x\Delta\dot{y} - y\Delta\dot{x}}{x^2 + y^2} \quad (B3)$$

and

$$\Delta\dot{\epsilon} = \frac{x\Delta\dot{x} + y\Delta\dot{y}}{c^2\epsilon} \quad (B4)$$

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